Bioreceptive brick façade

Incorporating plants into a dry-stacking masonry wall system

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Abstract

The current study focuses on the development of a new façade system which introduces greenery as part of brick walls. The main aspects of the proposed system are sustainability, moisture and materials, water supply and structure stability. The goal is to achieve a balanced relation among these aspects and reflect those into the product design. The current report consists of design and experimental research, aiming to explore the potential and tackle the challenges of designing a complete façade system. By identifying existing experimental and design research in relevant literature, a new green façade product is proposed. The stability of the system is based on a non-mortar solution, utilizing the Drystack® elements for the wall assembling. The design phases led to the integration of the system components, focusing on the use of a passive irrigation system. This is further analyzed with a building case study for better understanding its functionality and manufacturability. The different elements constituting the system, drystack, greenery, soil substrate and irrigation, are then decided based on theoretical research. Finally, experimental work is conducted in order to validate the project decisions and propose further improvements.

Key words: Drystack®, green façade, passive irrigation, soil substrate

Acknowledgments

My graduation project was achieved with a lot of hard work and also the help of certain people that I would like to thank deeply. Firstly, my mentors, who always provided me with useful remarks and who were anytime available to help me and advise me. Secondly, I would like to thank Erwin van Herwijnen from the TGS Company, without whom I would not have managed to finish my experimental work and who was always willing to help me and answer to all of my questions. Then, I want to thank Edwin Dijkhuis for providing me with information related to the plant species. Finally, I want to thank my family and my friends for standing by my side though all this process and any difficulties that I went though.

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1. Introduction

Greening the cities is gaining more and more attention in order to restore biodiversity into the built environment. Vertical green has become very popular in the construction world and there are multiple application techniques. Greening vertical surfaces can be achieved with plants, either rooted into the ground or in modular panels attached to the facade in order to cover buildings with vegetation (Ottelé, M. et al. 2011) Vertical green creates a good combination of nature and buildings in order to address environmental issues in dense urban surroundings. Vertical green can be classified into facade greening and living wall systems. Façade greening is based on the use of climbers attached themselves directly to the building surface, or supported by steel cables or trellis (Ottelé, M. et al. 2011). Living wall systems (LWS) consist of modular panels, each of which contains its own soil or other growing medium.

The walls on their own are generally an inhospitable environment for plants due to the high pH of the mortar in case of masonry or due to the density and pH of a concrete wall. This research tries to tackle the challenge of creating bioreceptive brick walls by changing their consistency in a way that plants could grow straight on their surface. Guillette coined the term 'bioreceptivity', which he defined as: "the aptitude of a material to be colonized by one or several groups of living organisms without necessarily undergoing any biodeterioration".Masonry walls are typically used for building surfaces and bricks have always been one of the most common materials, originally joined together with mortar. Bricks can vary in types, production process, colors and sizes. There are multiple methods of manufacture: mudbrick, fired bricks, molded, extruded and so on. They can be found in many applications in the built environment such as cladding, paving, garden wall and flooring. Bricks have been traditionally used for structural masonry in many countries and specifically in the Netherlands they constitute the most typical urban image.

Figure 1: Original brick wall (iStock / Bogdanhoda)

Bricks are originally connected with mortar and there is no much innovation in brick structure. However, there is a new masonry system developed and already applied, called the Drystack. Drystack has developed a system with bricks with drill holes where plastic strips with studs come to be attached. This allows for an easy stacking system that can be assembled and disassembled anytime, giving also the possibility for various combinations of the individual elements.

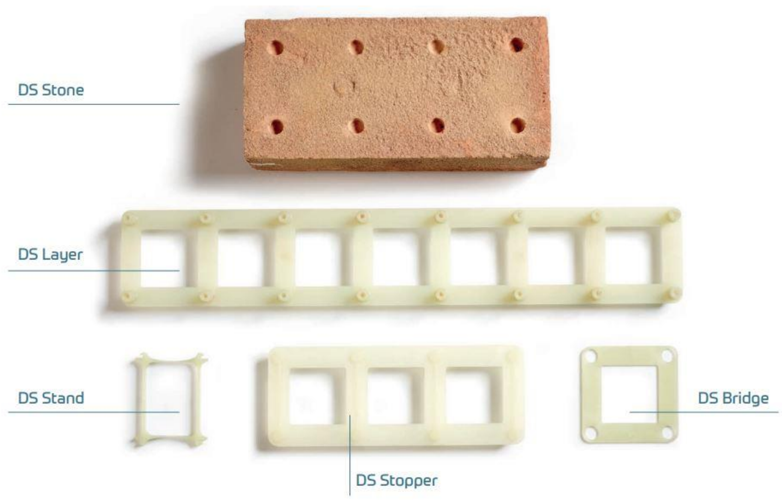

Figure 2: Drystack elements (Drystack BV < https://drystack.nl/>)

Figure 3: Drystack brick wall assembling (Drystack BV < https://drystack.nl/>)

Figure 4: Drystack sample (own work)

However, the current plastic connections allow only for straight placing of the bricks or 90 degrees angle to make corners. New ideas can be developed in terms of offering multiple possibilities to the drystack system. Moreover, the system could be further developed in order to introduce vegetation as part of the structure.

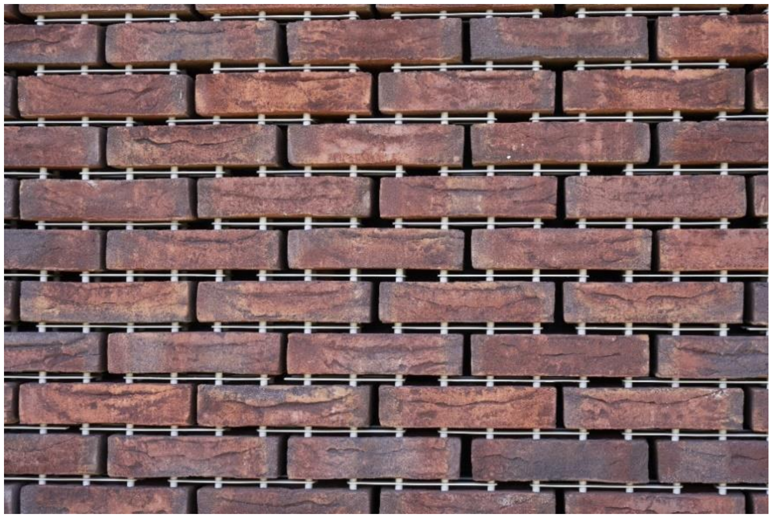

Figure 5: Drystack brick wall façade (Drystack BV < https://drystack.nl/>)

The problem that this research wants to tackle is the lack of urban greenery and also the fact that brick facades are missing functionality and innovation. The main goal is to propose a sustainable façade system consisting of bricks and plants, growing directly on the wall itself and which will be able to contribute to the urban biodiversity. The project focuses on creating a modular cladding product which uses the drystack technique and can offer environmental benefits, new design possibilities and an aesthetically good looking outcome. Additionally, the system should be characterized by simplicity and the production needs to be done with the least amount of energy in order to offer a sustainable product. This is further enhanced by the demountability and reusability of the elements.

The vision is defined by four aspects: First is sustainability focusing on urban biodiversity, second is flexibility offering new design possibilities, third is modularity meaning that all the elements can be easily separated and recombined and finally aesthetics defining the form of the outcome.

In this report, first the problem statement was mentioned, then the research questions are formed, which define the project and its direction. Afterwards, the literature study providing the research with useful information and ideas, is discussed and then the proposed system is analyzed. The design proposal is described and also an application example to an existing building. Then, products and materials are selected and discussed according to their characteristics. Finally, experimental work provides the research with realistic notifications and results.

2. Research questions

Main research question

- How can a brick façade system be composed in order to allow plants and building materials coexist efficiently on wall surfaces?

Sub-questions

- What ways can be found to facilitate natural growth of plants inside the system without risking the stability of the structure?
- What plants are more suitable?
- What kind of substrate should replace the mortar and offer the possibility for plant growth?
- How can water be collected, stored and distributed to the plants without causing any leak or damage?

5. Literature study

5.1 Experimental research

The first research field is based on experimental studies conducted to understand several factors related to vertical greening. This was achieved by studying various published papers and deriving knowledge through summary, classification and comparison of research studies that can offer relevant information and lead to solutions for the thesis project.

Firstly, the factors influencing bioreceptivity on masonry walls are researched. For a wall to become a hospitable environment for plants, certain variables should be taken into account. The building materials, moisture, wall age, accessibility, the pH value of the materials and wall dimensions are some of the main factors. The presence of water is highly crucial for plants to grow and materials with higher absorption, mostly porous materials could be considered more suitable. Surface roughness is another important factor and thus masonry walls can prove more beneficial instead of a monolithic structure (Lubelli et al. 2020).

Clay bricks, typically used in construction for centuries, they are very simply produced by mixing clay with water. Their water absorption is between 12% and 20% (CBA Claybricks). The percentage depends on the brick porosity. The risks of a very high moisture content are sometimes frost, decrease of mechanical strength, biological growth and an unhealthy climate in the interior, if it is a wall of a building.

In an experimental research exploring the influence of brick and mortar on the plant growth, the results showed that the brick with higher porosity, absorbs water better and faster. The two bricks tested are a soft mud molded brick with a frog (called the brick 2) and an extruded brick with 6 perforations (called the brick 8). Also mortars different in clay type and production process were investigated in terms of their binder ratio, grain size distribution of the aggregate, type of aggregate and type of binder (Lubelli et al. 2020).

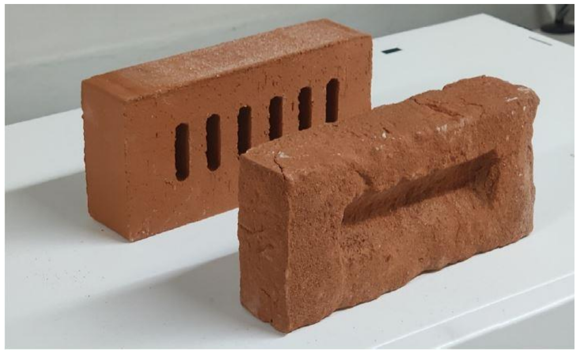

Figure 6: Brick 8 with perforations and brick 2 with frog (Lubelli et al. 2020)

Although the soft mud molded brick with higher water absorption is proven more suitable for plant growth, it provides less mechanical strength. Therefore, a solution needs to be found in terms of ensuring sufficient strength for the masonry and allowing plant growth at the same time. Additionally the plant roots may be another factor unsettling the stability of the masonry by damaging the mortar but this depends on the plant species (Lubelli et al. 2020).

If the structure did not depend mainly on the mechanical strength of mortar and bricks, then it could possibly allow plant growth without risking the stability of the masonry. Drystack system can be a solution to this because mortar does not play the main role of stability but this is taken by the plastic strips connecting the bricks. Thus, other binding material or any type of substrate could be used to make the intermediate layer. This could be chosen based on its porosity, its water absorption and its composition so that it can favor plant growth.

An impressive observation is that in many old masonry walls, plant growth takes place without any human or artificial interference. A research experiment conducted on a brick wall of an abandoned 115-years old building in Poland, showed how soil plants and a microbial community could grow on a vertical wall.

Masonry walls are an inhospitable environment for plant growth, as already mentioned in the introduction. However, over time, disintegration of the binding materials makes it possible to accumulate soot, dust, and other detritus from the urban environment in crevices, which in turn may allow early successive vegetation to grow (Trocha, L. K. et al. 2007). The creation of adequate plant environments is largely dependent on the degree of decomposition of mortar, concrete, or any other binding material.

In some countries like the Netherlands, in which urbanization and agricultural development have long since eliminated most of the natural habitats for plants "walls are often the only remaining habitats for plants belonging to floras which, in the course of urbanization and industrialization, have disappeared from the surrounding area" (Weber 1969).

The study which took place in Poland, examines the ecophysiology of silver birch (Betula pendula Roth). This species is tolerant of a wide range of environmental conditions such as temperature, soil chemistry, and soil pH (Trocha, L. K. et al. 2007).

Figure 7: B pendula trees growing on the brick wall of 115-year old building, Roots growing in the air-bricks (Trocha, L. K. et al. 2007)

The results indicated that plants growing on walls had higher foliar starch concentrations than those growing on the ground. Remarkably, the foliage concentrations of all nutrients were close to the optimum range typically found under natural conditions, despite the excesses or deficiencies of almost all available nutrients in the wall substrate (Trocha, L. K. et al. 2007).

One major factor enabling the establishment of silver birch under such conditions, is related to a very dispersal seed mechanism. Birch species are typically small sized, and they have the ability to disperse seeds over long distances. They belong to pioneer species meaning that they are hardy species which are the first to colonize barren environments (Trocha, L. K. et al. 2007).

One other aspect to be understood is how the plants could receive the proper amount of water needed. In the mentioned study, the plants sampled were between 1.6 and 3.5 m above the ground, thus it is unlikely that capillary action is responsible for bringing water up to them from the base of the wall. Most likely deteriorating down spouts, leaking into the interior of bricks caused by cracks in mortar and mosses can provide and maintain enough water for silver birch to survive (Trocha, L. K. et al. 2007).

This clearly proves that natural growth can take place on masonry walls but it is totally dependent on the wall consistency. The age of the building seems to play an important role because materials with time lose their properties and their strong cohesion. This allows other elements to enter the wall solidity and gradually enables natural growth. However, this goes along with the gradual impairment of the stability and it still remains to be solved how both stability and plant growth can coexist and create an efficient system. Additionally, the selection of plants plays an important role as well, considering that less water requirements and shallow roots can help to secure a good balance for combining structure and greenery efficiently.

Another important aspect of green walls is the irrigation and maintenance. In case of green façade systems, that plants are rooted in the ground or in plant boxes, water irrigation is quite easy. Water should be provided only at the base or in each plant box. Living walls are more complex because they are usually composed of a big variety of plants with various water requirements. (Pérez-Urrestarazu, L. and Urrestarazu, M. 2018). An irrigation system is commonly required that will be capable of delivering water to all the species throughout the whole surface of the wall and ensure the appropriate humidity conditions for plant growth.

There is a difficulty for adapting to species with different water needs, as there are problems in establishing hydrozones. The circulating flow and the working pressure are the main aspects to be taken into account (Pérez-Urrestarazu, L. and Urrestarazu, M. 2018). In order to avoid pipe obstructions and improve pressure equity, closed networks are advised. Localized irrigation works better for living walls. One of the most common irrigation options for living walls is to place drip lines (figure 8) at different heights so that water can move vertically and laterally in between line by gravity and lateral diffusion (Pérez-Urrestarazu, L. and Urrestarazu, M. 2018). Such a system could be totally artificial or it could rely on canalization of rain water, thus exploiting a natural source for the water.

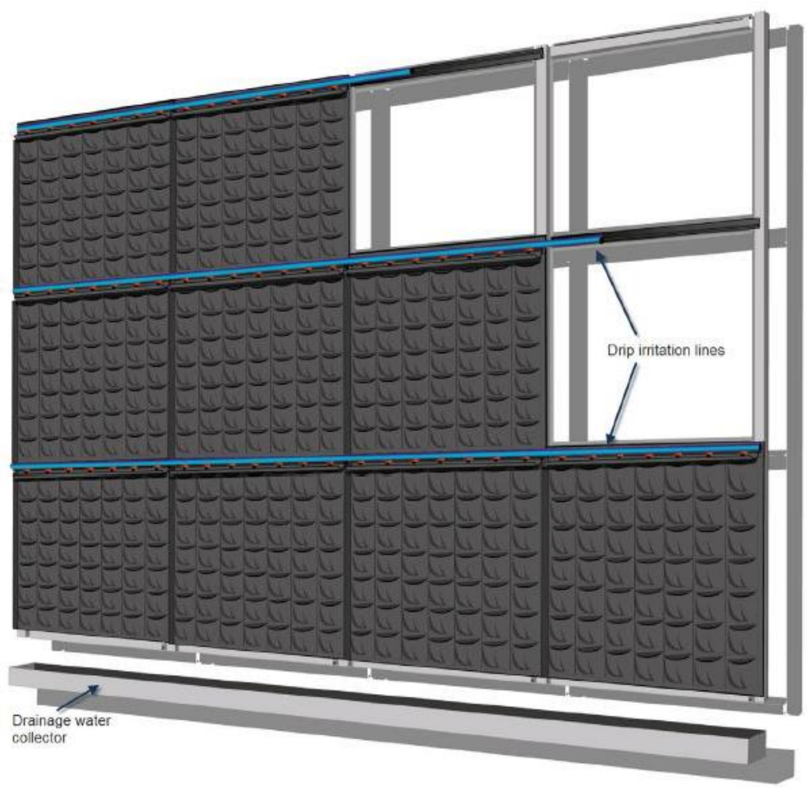

Figure 8: Irrigation system (Pérez-Urrestarazu, L. and Urrestarazu, M. 2018)

The water amount provided by the irrigation system should be controlled so that it does not exceed a certain level. The drainage capability of the substrate used for a living wall is very important while it must retain water and at the same time avoid saturation.

Moreover, efficient water management is crucial and in order to avoid drainage or excess of water, the irrigation schedule should be very well performed. An optimal irrigation operation happens when there is sufficient water supply with the least amount of losses. The irrigation requirements depend on several factors such as location, light conditions, temperature and humidity, plant species and substrate used. The initial moisture conditions of the substrate also affect the irrigation performance (Pérez-Urrestarazu, L. and Urrestarazu, M. 2018). This means that for the current project, the substrate aiming to replace mortar should be able to retain water but at the same time also allow it to flow. The bricks can also assist moisture absorption, not only due to their materiality but also adding a frog could work as a storing space for water. Keeping in mind the goal of achieving a circular irrigation system, moisture levels and rainwater harvesting are very crucial.

Last but not least, the environmental footprint of a new system should be of prior attention. In a research done by Marc Ottelé, Katia Perini, A.L.A. Fraaij, E.M. Haas and R. Raiteri, four green façade systems are criticized in terms of their sustainability. A conventional built up European brick façade is compared to a facade greened directly (only with a base on the ground level), a facade greened indirectly (supported by a steel mesh), a facade covered with a living wall system based on planter boxes and a facade covered with a living wall system based on felt layers.

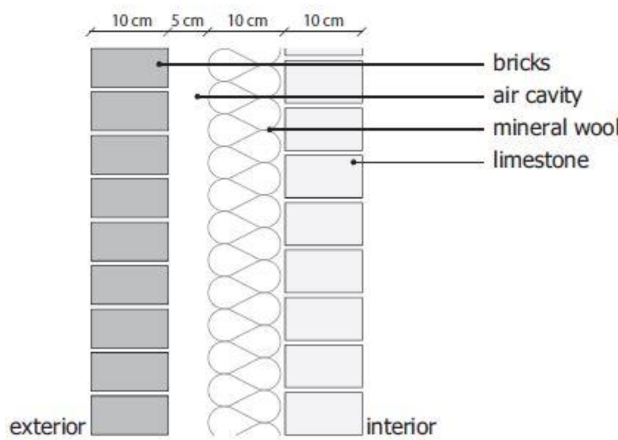

Figure 9: Bare wall with material layers (Ottelé, M. et al. 2011)

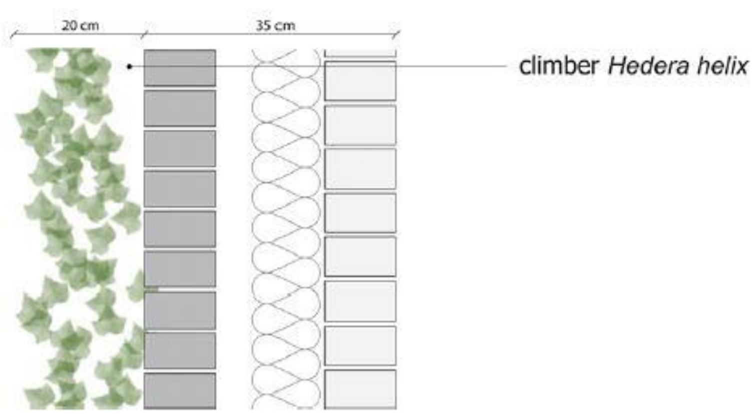

Figure 10: Direct greening system with material layers (Ottelé, M. et al. 2011)

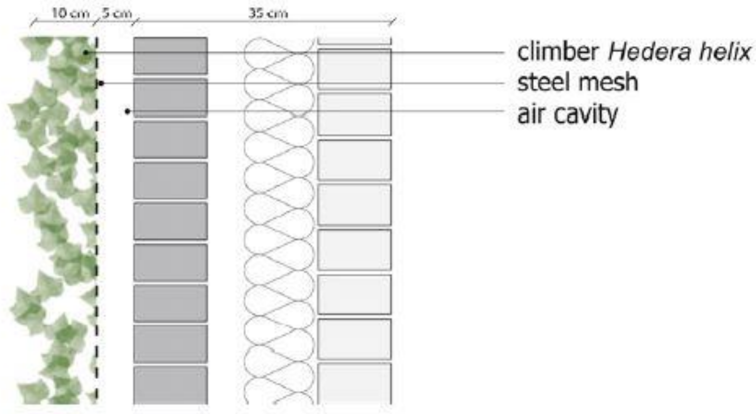

Figure 11: Indirect greening system, with material layers (Ottelé, M. et al. 2011)

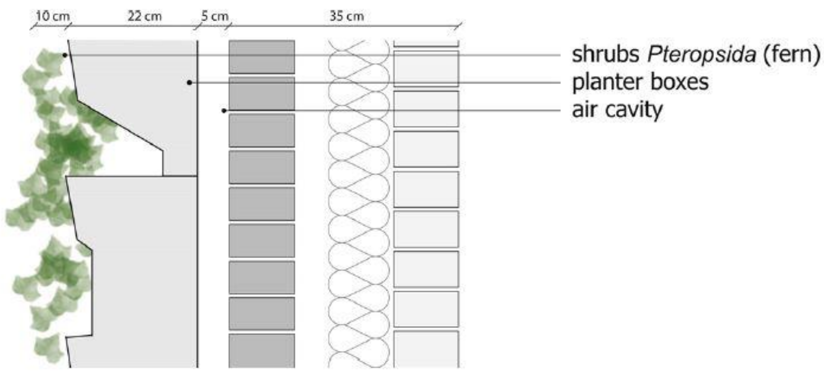

Figure 12: LWS based on planter boxes with material layers (Ottelé, M. et al. 2011)

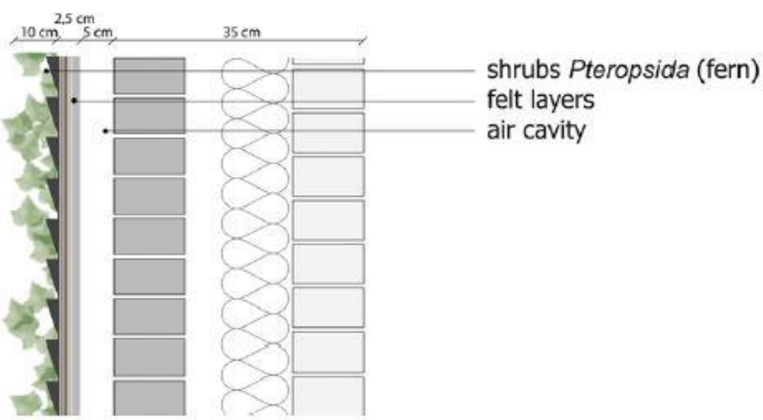

Figure 13: LWS based on felt layers with material layers (Ottelé, M. et al. 2011

The sustainability for these solutions is assessed by three main factors: materials, transportation and waste. The results show that the direct greening system has the lowest environmental burden. The indirect greening system has a high impact profile for the supporting system due to the use of stainless steel. The highest environmental burden that is found regards the living wall system based on felt layers because it is difficult to recycle the panel (Ottelé, M. et al. 2011).

The study also discusses the environmental benefits related to two types of climate, Mediterranean and temperate. For the Mediterranean climate less annual energy consumption for heating is needed, so the energy saving thanks to the greening systems has a lower impact on the positive environmental profile while on the other hand the cooling potential of vegetation plays an important role for the indoor comfort with energy savings for air-conditioning. For the temperate climate the environmental burden profile is higher than the energy savings for heating for all the greening systems, except for the direct greening system that the environmental burden is lower than the environmental benefit profile (Ottelé, M. et al. 2011).

Considering that the direct greening system has the smallest influence on the total environmental burden, it can be understood that the less materials and substructures used for vertical green, the more environmentally friendly the system is. Besides, if the elements used are recyclable or reused, then it can also make a circular solution. Therefore, materials and process should be carefully selected to secure the sustainability of the system. Nevertheless, the goal of this research, to make plants part of the wall itself, resembles a direct greening system which seems to be beneficial for the environment.

5.2 Design Research

The second research field focuses on design approaches and innovations related to vertical greenery. Ideas relevant to the current project are researched to study existing techniques and their efficiency.

First of all, a project closely related to the current one, is the KIEM "Wall Garden" project, currently running at the Faculty of Architecture, which aims to an integration between masonry quay wall and vegetation. The composition of the masonry wall consists of bricks and a dry-stacking system. Strong polyamide elements interconnect the bricks, providing strength to the masonry without the need for mortar. Thus, the gaps in between, traditionally containing mortar, are to be filled with compost material that offers the perfect substrate for plants to grow and also a buffer for water storage (Wall garden 2020)

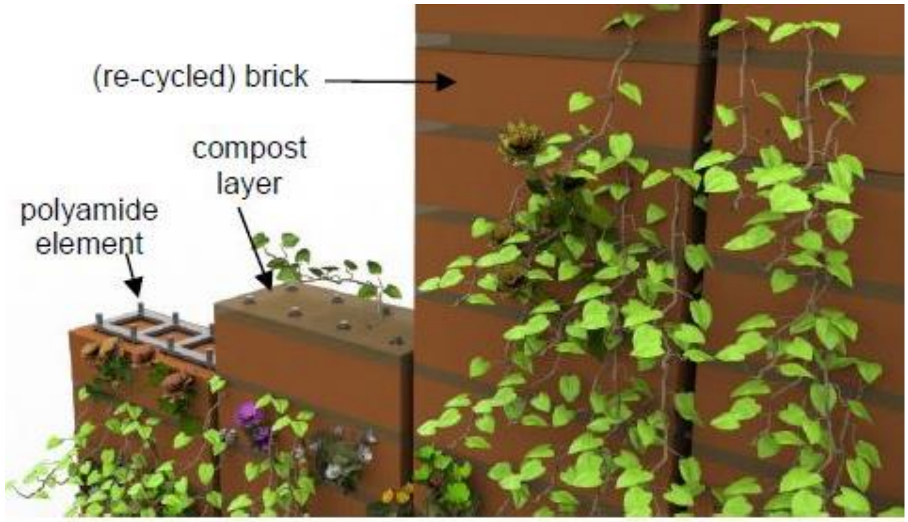

Figure 14: KIEM design proposal (Wall garden 2020)

This system contributes to circularity, allowing for easy reuse of the bricks, which can be efficiently detached from each other. The polyamide elements can also be demounted and reused and the whole system is very easy to build up and disassemble if needed. The compost layer replacing mortar is independent from the structure and ensures better stability.

The feasibility of this idea is being explored in quay walls. However, applying this idea as a façade system includes more risks. The comfort standards of the inner space of a building, as well as the structure stability are crucial and high moisture levels of the façade may affect those negatively. Thus, water tightness and drainage are very important, as well as structural brackets and interconnecting elements keeping the system stable.

During the literature research, certain innovative products were found, which are seeking solutions of incorporating greenery in their structure.

Betoconcept represents a list of vertical landscaping products. Instead of simple strict structures, these products offer the possibility for attractive vertical landscapes with a big variety of plants and colours. This is applied mainly for retaining walls and the addition of plants helps reducing the noise levels. The Betoconcept proposes a range of different shapes, textures and styles that accommodate planting on walls, no matter the size. The range includes interlocking blocks made of high-strength pressed concrete machines, providing dry building solutions and noise absorption, excellent for urban and rural external wall solutions. Dry built blocks interlock to form the required face angle to provide space for the plants and they are easily constructed with a plantable substrate or a stone-faced finish. Good drainage and water capture thanks to the protractions of the blocks also helps keeping the maintenance requirements to a minimum. Using landscaping depth ensures that substantial growth can benefit both sound suppression and help achieve rapid results in landscaping over a large wall area (Grass concrete 2020)

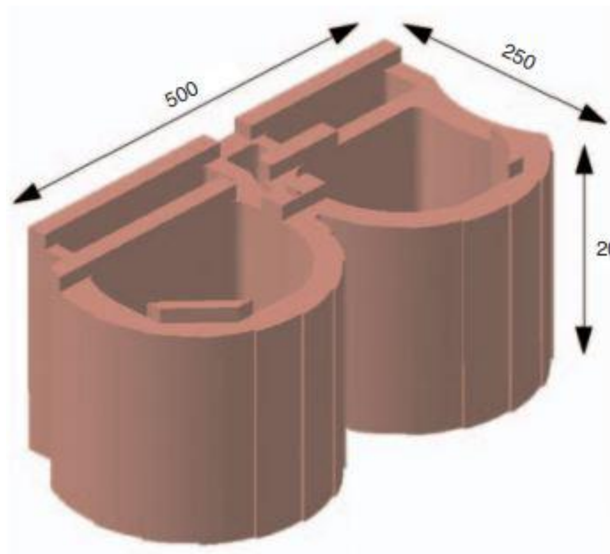

Figure 15: Betoplus plant boxes (Grass concrete 2020 <https://www.grasscrete.com>)

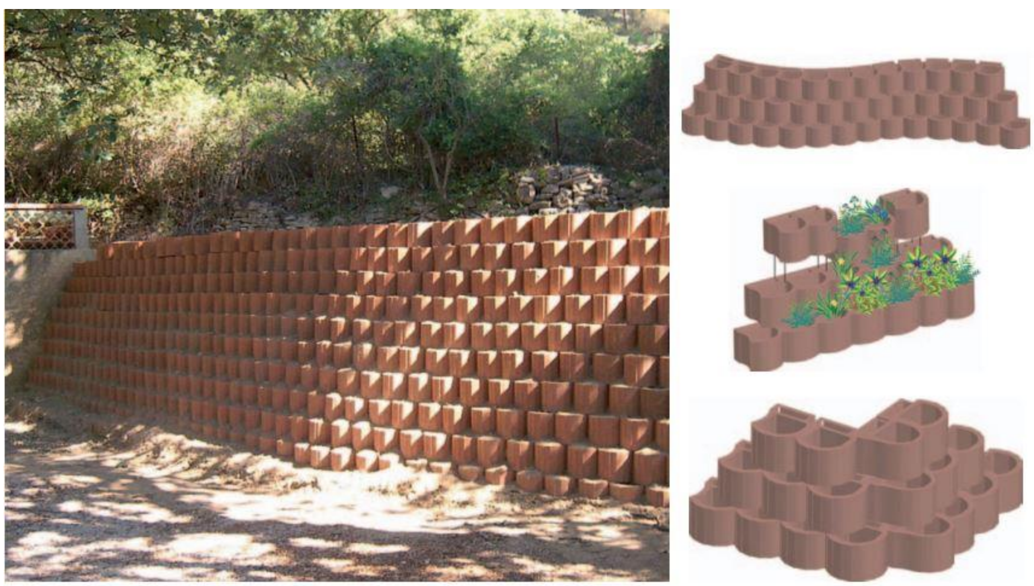

Figure 16: Betoplus assembling and application (Grass concrete 2020 <https://www.grasscrete.com>)

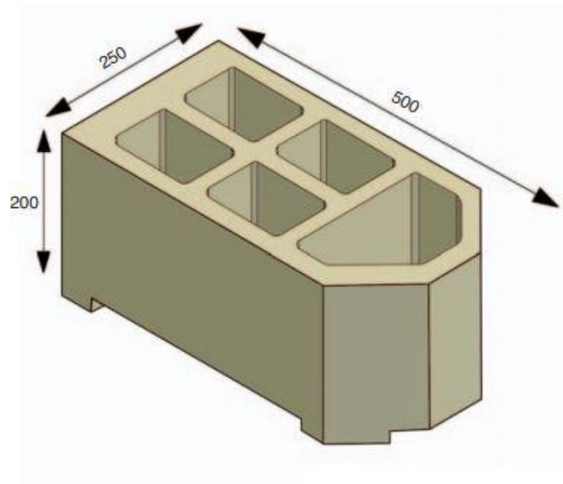

Figure 17: Betoatlas plant box (Grass concrete 2020 <https://www.grasscrete.com>)

Figure 18: Betoatlas application (Grass concrete 2020 <https://www.grasscrete.com>)

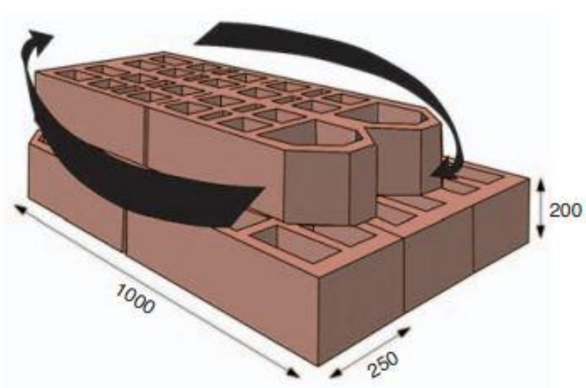

Figure 19: Betotitan plant boxes (Grass concrete 2020 <https://www.grasscrete.com>)

Figure 20: Betotitan application (Grass concrete 2020 <https://www.grasscrete.com>)

Regarding the thesis project, these applications offer various ideas and solutions for the challenge of growing plants vertically. Appropriate spaces, protractions or recessions, curved surfaces, interlocking units and assembling in multiple angles, these are important factors for achieving an interesting and flexible façade system.

Another similar product is the Keystone retaining wall system consisting of modular concrete units for the construction of conventional reinforced soil retaining walls with or without a mass or reinforced soil, stabilized by horizontal layers of geosynthetic reinforcement materials (LLC 2017). The Keystone Plantable Retaining wall Blocks are designed with an innovative planting system, allowing vegetation to be grown directly from the wall face. Based on the Keystone retaining wall blocks, the plantable system provides a planting cavity, space for drainage and root growth, and a specialized channel for running irrigation lines. There is a freedom in design because the system can be customized according to the requirements of each project and each row of blocks always steps back a certain distance from the one underneath it. The flexibility of this system makes it very suitable for straight, curved and terraced retaining wall systems.

Figure 21: Keystone planting retaining wall system application (LLC 2017 <https://www.keystonewalls.com/products>)

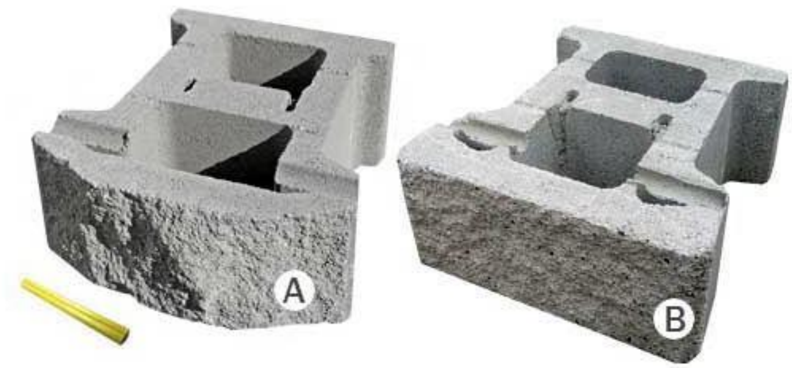

Figure 22: A. Triface, B. Stone face (LLC 2017 <https://www.keystonewalls.com/products>)

This project makes a clever combination of greenery and concrete blocks that give an interesting landscape as an outcome. The holes hidden inside the blocks offer the requiring space for the plants to grow and they can maintain adequate moisture. On the sides of the blocks there are recesses on the concrete to secure the path for the water reaching the plants. Therefore, the system is quite simple because the blocks are shaped and processed in a way to cover the needs for the plants without extra subsystems. This can offer more sustainable solutions and the idea could be further integrated and used for the current thesis project.

Another very useful and informative project explores the methods and materials for creating green quay walls in Houthaven in Amsterdam. The Houthaven, about two kilometers west of Amsterdam Central station, has gained the interest of the municipality and of a large number of developers. It is an emerging area, aiming for sustainable living and working opportunities and it is expected to be ready in 2023. The area will also be used as a residence for nature. In addition to habitats for birds, bats, insects (nesting boxes, winter quarters for bats, insect hotels, etc.), climate-adaptive greenery is being developed, whereby parts of the quay walls are also greened.

Figure 23: Vision for Amsterdam quay walls, (Ton Denters et al. 2019, 'Visual door ingenieursbureau Amsterdam')

Commissioned by the Houthaven project group, the Amsterdam engineering firm has developed a basalt[1] wall construction with a layer of substrate, able to transport water, on which wall vegetation can develop. The plants are embedded into the masonry with roots into the soil substrate behind the wall. Perennials are used to offer a fast green and blooming image after planting because it would take many years for plants to emerge on a wall naturally (Ton Denters et al. 2019).

Choosing the type of mortar was very important and the challenge was about reducing its pH value to enhance plant growth. It was suggested by experts to reduce pH through accelerated carbonation (reaction of Ca(OH)2 (calcium hydroxide) present in lime and cement mortar, with CO2 from the air). This can be achieved in a wall by wrapping the construction with foil and blowing a CO2-rich gas behind it (Mr. J. Steketee). The gas could be pumped around and continuously add CO2 (control based on concentration). The reaction starts on the outside and the front slowly moves up. The progress of the process can be monitored by test pieces and by occasionally drilling or cutting out a piece of mortar and coloring this with a pH indicator. This procedure was considered very time consuming, expensive and difficult to monitor. It is better to derive first the results through laboratory tests.

The reaction starts on the outside and the front slowly moves up. The progress of the process can be monitored by test pieces and / or by occasionally drilling or cutting out a piece of mortar and coloring this with a pH indicator. The color change is easy to follow. You can view this in the field or in the lab.

In addition, it was investigated how the moisture balance can be optimized, including how water can rise through capillarity from the water surface to the substrate.

Finally, it was also researched, which plants can survive under the certain conditions and how they can be best placed in the basalt wall.

All these were explored in the mock-up quay wall (figure 25). The two types of soils, supplied by two different producers, BVB and TGS substrates were compared in terms of their characteristics. The main factor was capillarity, the ability of water rising to a certain height against gravity. The goal was to supply the plants with the required amount of water, using the water of the canal thanks to capillarity.

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[1] Basalt is a fine-grained extrusive igneous rock formed from the rapid cooling of low-viscosity lava, rich in magnesium and iron exposed at or very near the surface of a rocky planet or a moon.

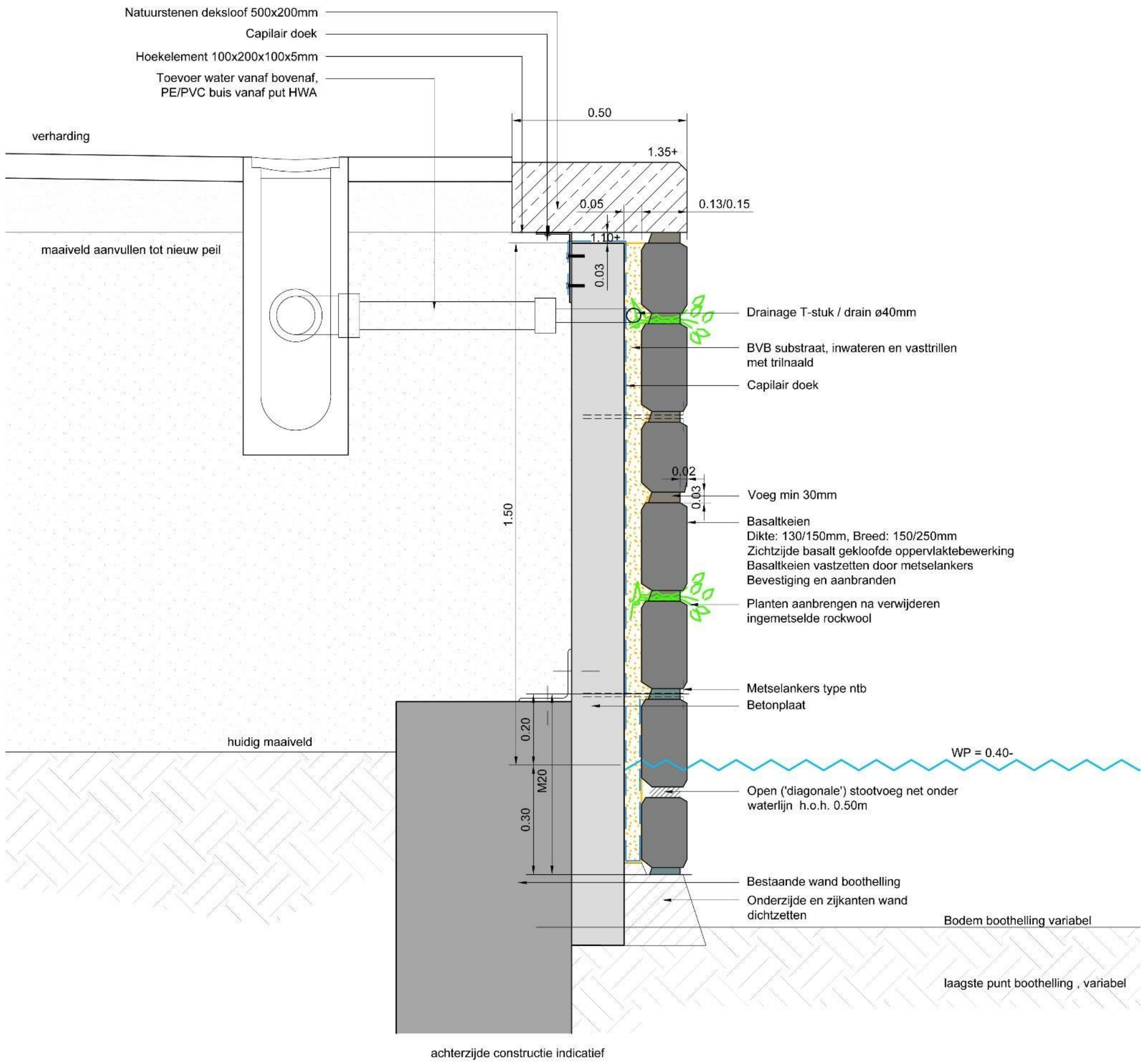


Figure 24: Section detail of the quay wall (Ton Denters et al. 2019, 'Tekening 18.T0583-T140')

The construction of the quay wall took place in September and October 2018. After the test setup, monitoring and assessment of the plant development and the moisture of the wall were carried on for some months.

Figure 25: Mock-up quay wall (Ton Denters et al. 2019, 'Foto's d.d. 13-05-2019')

The monitoring indicated that the moisture content up to one meter above the water level is the same for both substrates tested. However, in case of the TGS substrate, the plants higher than one meter were the least vital and the substrate was dry. Its capillarity does not reach the desired 2 m height, differently than in the case of BVB substrate. It was also recommended to install a drain at the top of the substrate and connect it to a rainwater drain from the pavement. In this way, after a rain shower, the substrate can receive water directly from above and allow the plants in the upper part of the quay wall to develop better (Ton Denters et al. 2019).

With regard to the choice of mortar, the selected one consists mostly of sharp sand, cement and also finely ground trass (Ton Denters et al. 2019). The fact that the plants do well in the test wall is not related to the choice of mortar. The species are in fact "separate" from the mortar in soil containing plant holes. With this choice of mortar, the non-planted wall parts may eventually become overgrown.

Moisture content in the wall is an essential factor for wall plants and is therefore a crucial point of attention in wall restoration. In old, somewhat weathered walls with soft lime mortar, moisture easily penetrates the wall. So-called soil-retaining walls (these walls are fed with moisture from the underlying soil body) are particularly promising. The humidity level also depends on the orientation, with walls facing north in particular being moist and therefore promising for wall plants.

Shading a wall, especially if it faces south, stops evaporation and promotes the germination and growth of plants. The presence of planted trees is therefore beneficial (Ton Denters et al. 2019). On the other hand, too much leaf litter on sloping wall surfaces can have a negative effect. Shadow can also be caused by, for example, bumper beams on a quay wall.

To sum up, If these factors are taken into account in the (re)construction of walls, beautiful wall vegetation can be expected in about 15 to 25 years. If faster results are needed, additional interventions are required, such as planting species and optimizing the moisture balance (irrigation systems).

5.3. Summary of the Literature Study

The literature provided and discussed creates a brainstorming for the project in order to proceed to the definition of the final product, the materials and their composition and the design of the separate elements.

Summarizing the useful information given in this literature research, the main factors that need to be taken into account are the water absorption of the materials, the irrigation system, the selection of plants and soil substrate, while also the modularity and sustainability of the system.

Moisture levels are very important and largely depend on the chosen materials and their properties. Irrigation should make sure that all plants receive the required amount of water to grow properly. Rain water can be used by storing and canalizing it. Plants selection is also important because their characteristics vary and it is wiser to opt for plants with similar requirements. The substrate on which they are going to grow is also crucial and needs to be carefully chosen to enable prosperous plant growth and at the same time secure a stable structure. Modularity is another key element of this project, achieved with the dry-stacking system, which enables all the elements to be easily demounted and act as separate components.

Finally, the project aims to restore urban biodiversity and replace the original simple brick facades with new brick claddings full of greenery, offering a unique outcome. Sustainability can be ensured by the simplicity and restriction of elements, by the reusability and demountability of the elements and finally by the thermal and natural properties plants can offer.

6. System design

The proposed system consists of certain major design elements. These are the bricks, the drystack plastic elements and the substrate filling the gaps. The design started with exploring various configurations of brick placing and the possibilities of drystack. The aim was to find the simplest solution in terms of materials and elements used but at the same time create an interesting pattern. The façade design includes also the watering system which is very important and becomes a key factor to lead the design options.

6.1. Preliminary design idea

Taking everything into consideration, the first thoughts of the product design can be discussed. Various configurations of the drystack elements are explored to enable flexibility and design freedom.

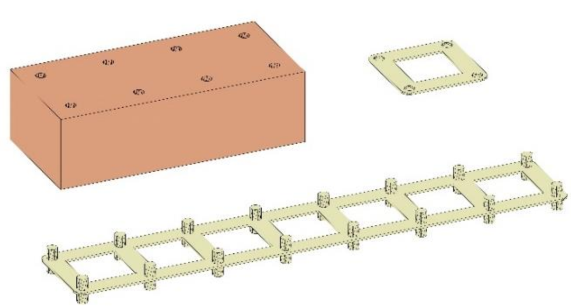


Figure 26: Main drystack elements (own work)

Using the drystack elements and placing some bricks perpendicular to the wall in a random order, offers various patterns and gives a texture to the façade. The protruding elements can also be helpful for collecting the rain water.

The bricks used for the drystack system have to be provided with small holes where the plastic strips are attached to hold the structure stable. As it has been already discussed, bricks with frog can store moisture and they can be favorable for plant growth.

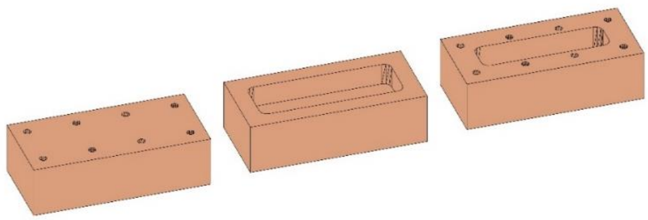


Figure 27: Comparing brick form options (own work)

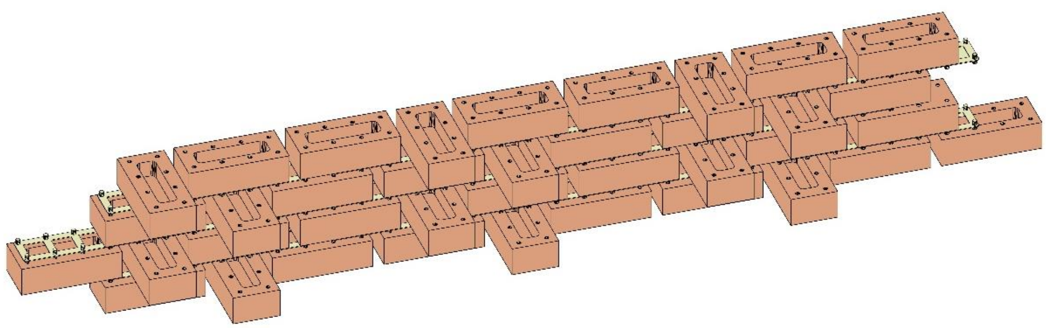


Figure 28: Initial configuration of bricks placing (own work)

Figure 29: Adding plants to the system (own work)

Adding plants to the system creates a complete overview of how a façade could finally look like. Interesting patterns made by the elements together with the colours and the textures of the plants offer a beautiful and almost natural outcome.

In the design aspect shown in figure 29, bricks work more like plant pots, which is not what the system was aimed for, also not fully utilizing the possibilities of drystack. The material in between the bricks should work as a substrate for the plants to grow. Moreover, a simple and passive irrigation system should be proposed to make the living system work as naturally as possible.

6.2. Design proposal

Going further on with the design, the assembling and the brick placing are being explored together with the watering system.

Firstly, it was decided that certain bricks will be placed perpendicular to the wall so that they could receive water easily and transfer it to the soil substrate. However, the protruding bricks cannot be chosen randomly. There should be a logic concerning the optimal position for watering all of the soil mass effectively. At the same time, the façade pattern should be interesting also in terms of aesthetics. The protruding bricks have frogs to receive and store the water, which then should get transferred to the soil substrate.

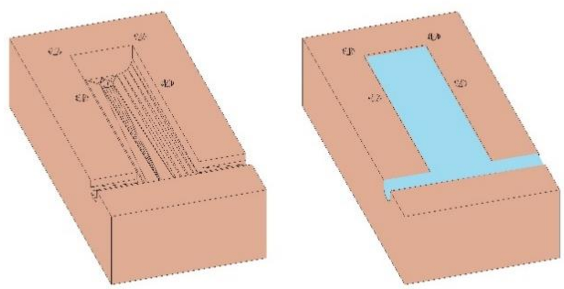


Figure 30: Protruding bricks (own work)

Seeking the best design solution, the process and the stages worth to be mentioned. Figure 31 indicates the process with the different patterns explored before reaching the final solution.

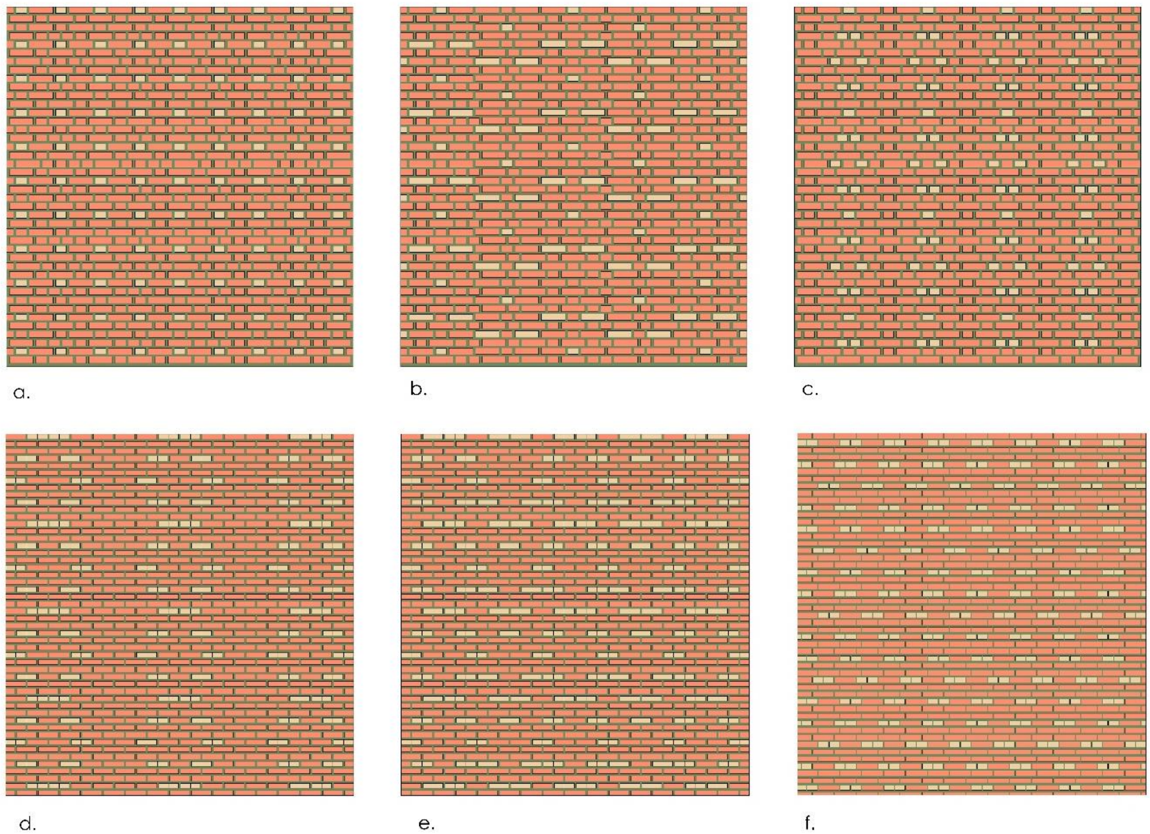


Figure 31: Patterns of the design process (own work)

Starting with pattern a, the protruding bricks are placed with a certain grid and form straight vertical lines. For this solution, not only the normal size of the bricks is used but some bricks are cut in half or in 3/4. This offers diversity and flexibility in designing. However, cutting the bricks demands time and work, adding also complexity to the system. Additionally the protruding bricks work as individual water elements, while there could be a way that they cooperate with each other making a connected watering system.

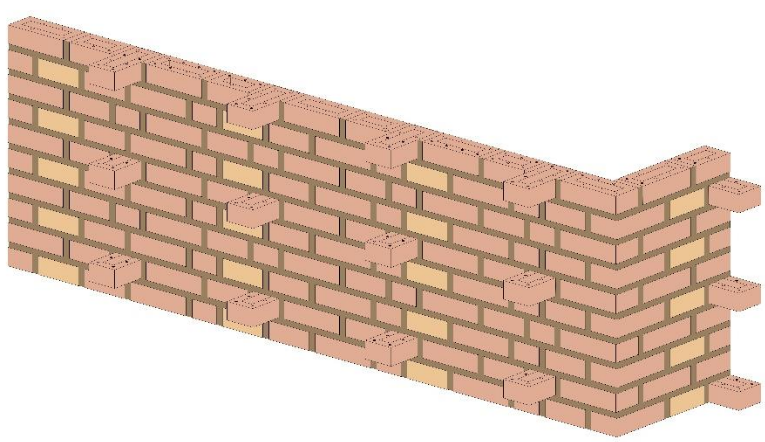


Figure 32: Axonometric view of pattern a (own work)

Then moving to the pattern b, bricks are restricted to normal size and halves. The pattern of protruding elements consists of both parallel and perpendicular to the masonry bricks that can move the water from one to the other and create a natural gradual flow on the surface. The disadvantage of this solution is that the horizontal protruding bricks may risk the stability of the structure.

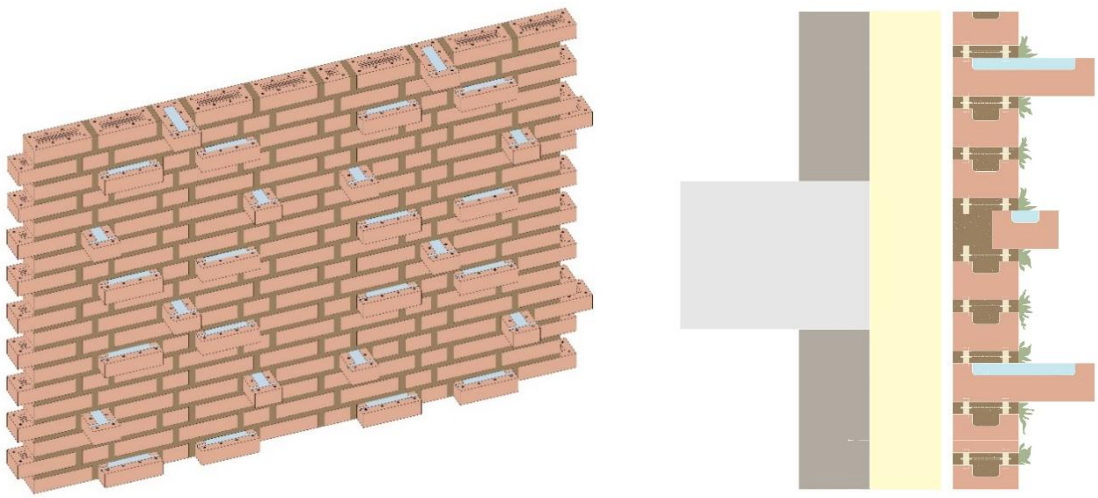


Figure 33: Axonometric view of pattern b, section detail of the wall (own work)

Pattern c offers an alternative design with only vertical bricks protruding. However, cutting bricks into halves is still time and energy consuming and thus the system needs to be further simplified.

In pattern d, only the normal size of the bricks is kept to be used and the protruding bricks are coupled or they are placed in fours. The groups of bricks receive the water and then they pass it into the soil or to the next group of bricks below. Nevertheless, the bricks being responsible for the watering, need to be arranged accordingly so that they transfer similar amount of water to all of the façade surface. This is important for the plants to grow properly and receive the water amount needed.

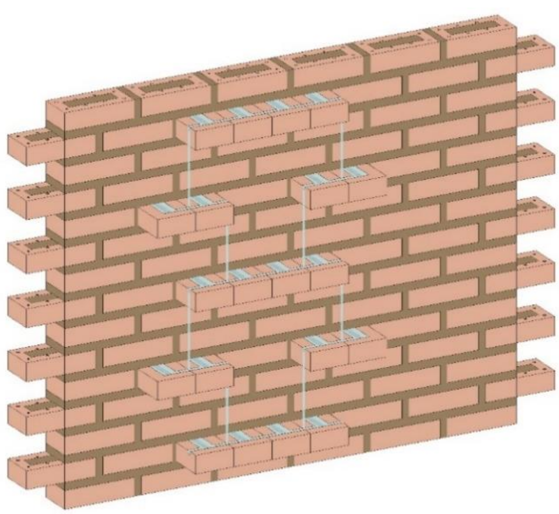


Figure 34: Axonometric view of pattern d (own work)

The pattern e represents a good option for spreading the water equally on the façade. At the same time, an interesting pattern is created, making various shapes on the wall.

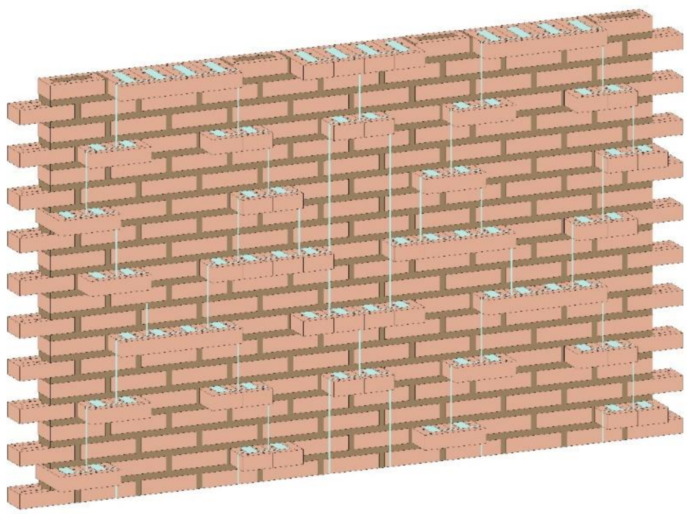


Figure 35: Axonometric view of pattern e (own work)

The protruding bricks have certain cuts in order to lead the water direction. One part of the water needs to be transferred to the next protruding bricks below and the rest should pass through the brick into the soil. Therefore, there are two notches on the outer side of the frog, which do not reach the bottom of the frog and there is also a small through hole on the bottom of the frog on the other side. This way, when the brick receives water, it will quickly exit through the notches, while the remaining amount will exit from the small hole and moist the soil. This becomes a crucial element of the design and the irrigation system.

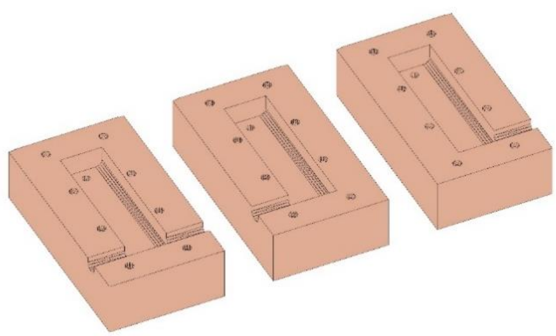


Figure 36: Protruding bricks configurations for pattern e (own work)

The disadvantage of solution e is that groups of four bricks are difficult to arrange the water flow efficiently from one to the other. In addition, they require cutting different notches depending on the brick position and this adds a certain complexity to the system. It is better to solve it with only one type of perpendicularly placed brick.

Finally, the pattern f makes the optimal solution for the system. Only groups of two bricks are placed vertically and in such a way that water can smoothly move downwards to all of the façade and spread equally. Moreover, the elements used are even more restricted making the system as simple as possible. Only the normal size of the bricks is used and the notches are the same for all the protruding bricks. This makes the manufacture process easier and faster. One type of brick is used and two types of forming are only required, one for the horizontal and one for the vertical bricks.

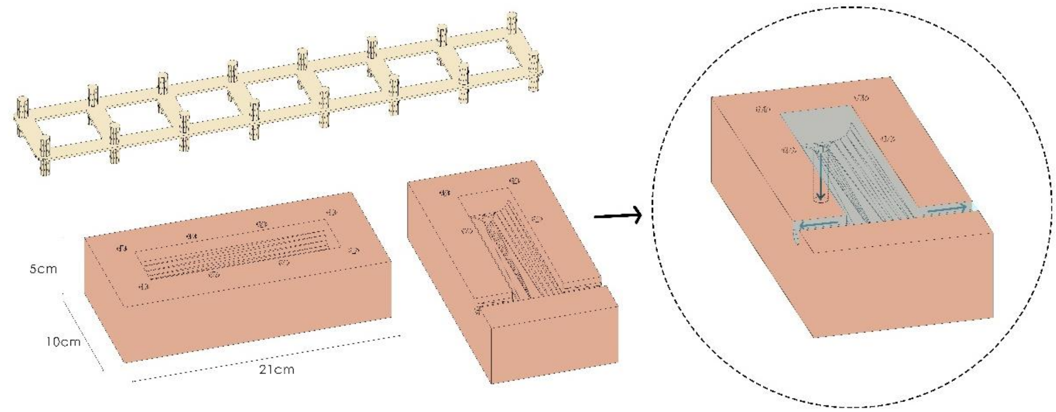


Figure 37: Main elements of the system (own work)

Then, the assembling of the elements is also fast and easy. The couples of protruding bricks are placed with a specific repetition and there is no complexity in construction.

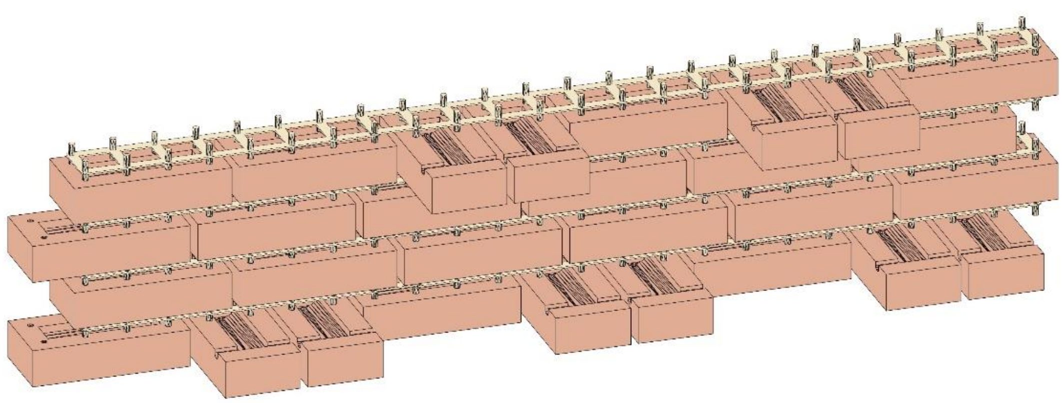


Figure 38: system assembling (own work)

The bricks protruding of the wall receive water either by rainfall or from a water reservoir placed on top of the system to supply the façade in case of dry periods. Water is expected to spread through the cuttings on the bricks and cover all of the façade filling the protruding frogs with water, which then passes inside the soil (figure 37). This can secure a prosperous plant growth and achieve the goal for a natural colorful wall surface.

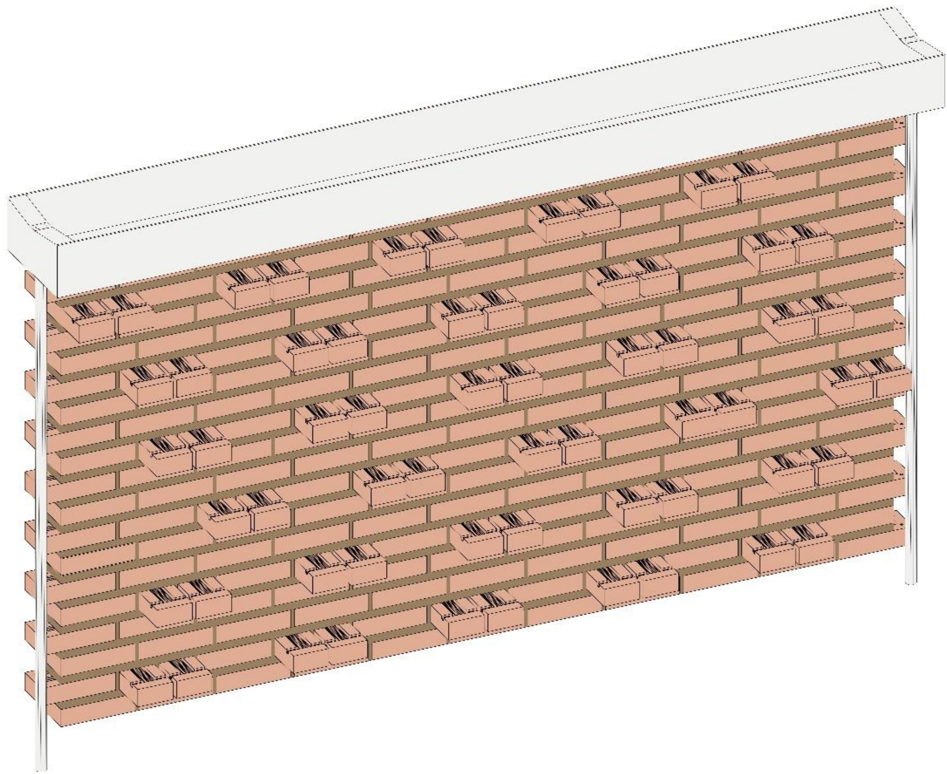


Figure 39: Axonometric view of the system (own work)

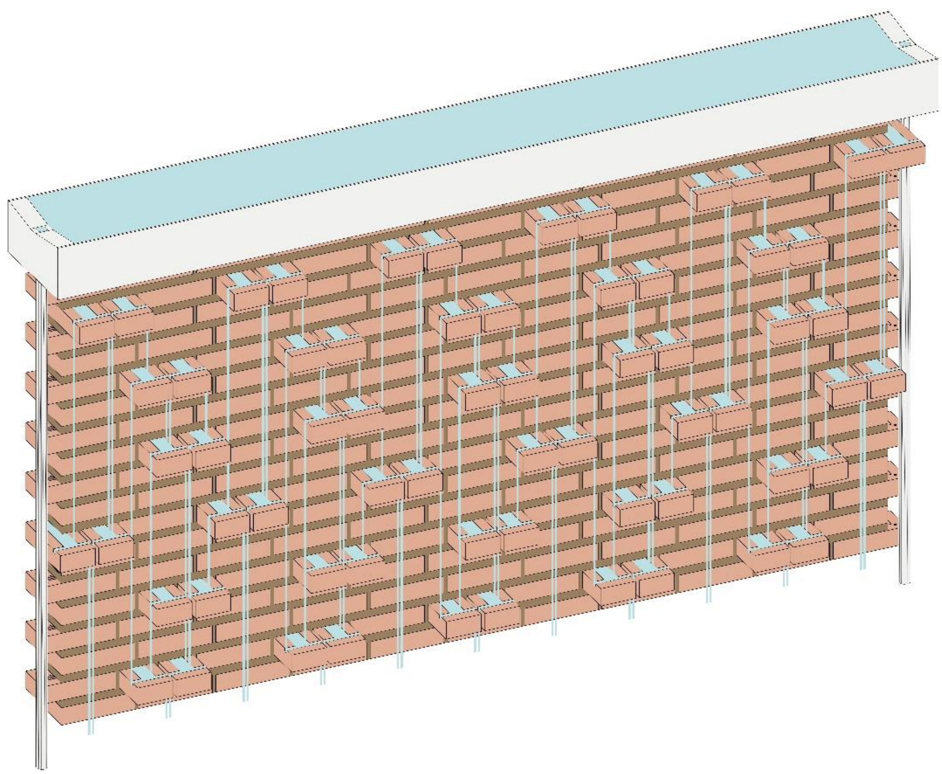


Figure 40: Watering system (own work)

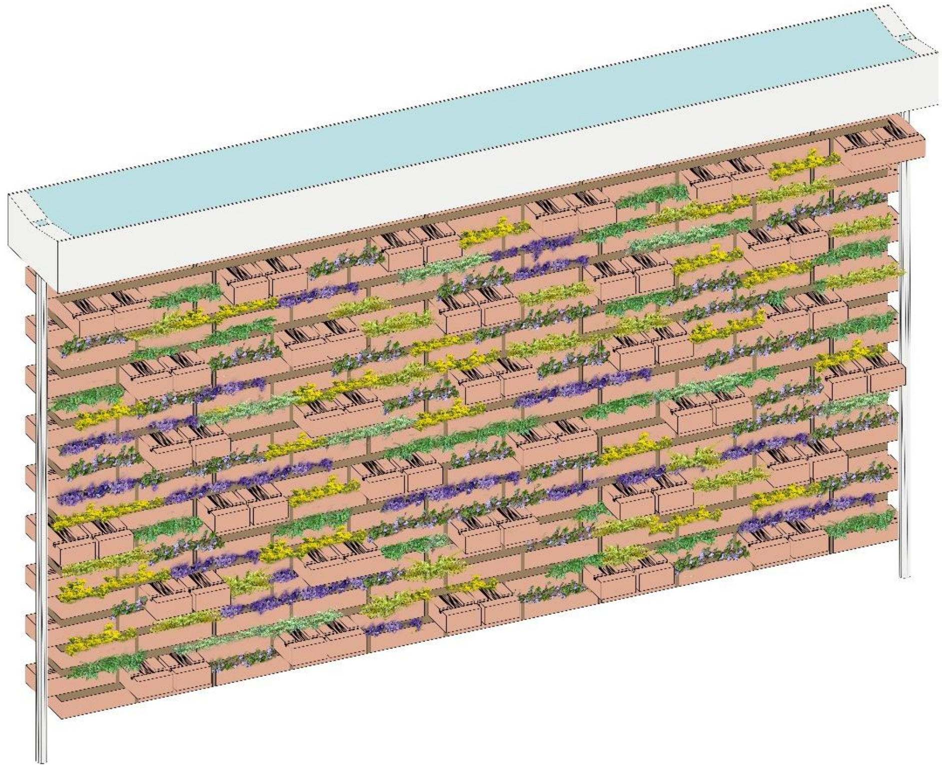


Figure 41: Plant growth (own work)

7. Building case study

For better understanding the use of the system, a building from the 70's was chosen as an example to replace the existing brick cladding and solve all the occurring challenges. The building skin was examined and also the possibility of adding the new system and attaching it effectively on the existing structure. Drawings were provided from the city archives and they were used for the designing of the renovation.

Figure 42: Pictures of the building (own work)

The building, shown in figure 42, is a typical Dutch construction of the 70's, with a typical brick façade, a thick inner wall of calcium silicate brick and without insulation. The reason of choosing a building of this period is that its structure is old and requires renovation. This building also belongs to the typical Dutch social housing, which were low-cost constructions and their façade possibly requires renovation in order to meet the comfort standards and improve its performance.

Apart from its better performance, the building could transform to a natural scenery inside the city. Its façade can become a colorful surface with texture, patterns and multiple plants.

Figure 43: Zoom photos on facade detailing (own work)

Figure 44: Edited drawings (Delft city archives 1981)

Going into more detail, the layers of the wall are indicated in figure 45. Adding insulation increases the total thickness of the wall, meaning that the foundation may require certain reinforcement and material addition.

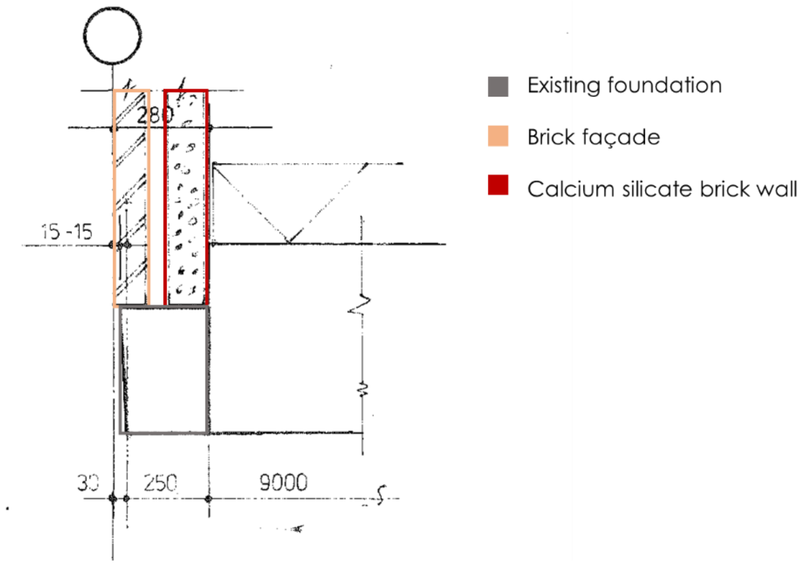


Figure 45: Foundation detail (Delft city archives 1981)

Extra concrete is attached to the foundation in order to create a stronger base for the brick cladding wall (figure 46). The upper concrete piece also consists of drilled holes to receive the plastic strips. In order to reach the required thickness, excavation is needed for the concrete addition, which is casted on site. Then, one last concrete piece is added on top and this is where the cladding gets fixed. The stability is then secured by steel reinforcement connecting all the pieces together and set in the existing foundation.

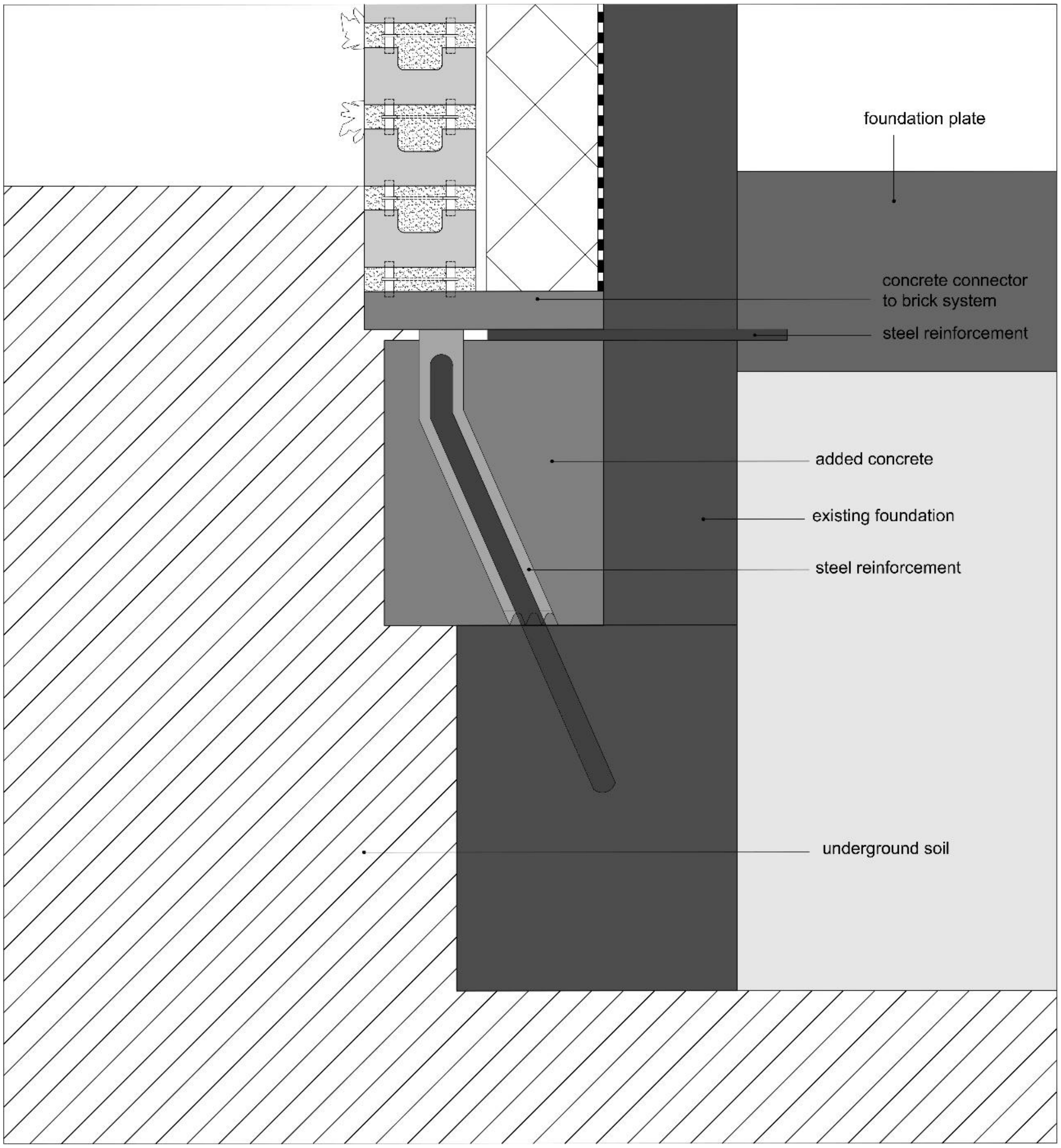


Figure 46: New foundation detail (own work)

The stability of the cladding depends also on its connection with the existing wall. It has to be well attached to it and this can be ensured by bolting it into certain points. A steel profile is placed on top of the protruding bricks to stabilize the soil and this can be bolted inside onto a steel bracket with a flexible joint, which interrupts the insulation and transfers the loads of the cladding to the interior wall structure (figure 47).

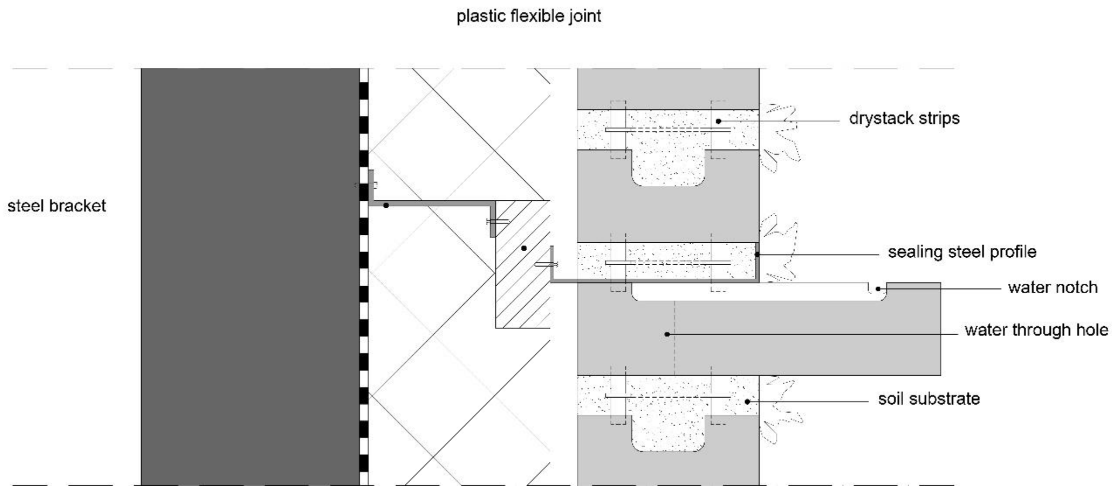


Figure 47: Detail for wall and cladding connection

In the cross-section drawing of figure 48, the different layers of the wall are clear. Going from the inside to the outside, first there is the existing wall of calcium silicate brick, then a sealing membrane that works as a barrier for moisture and then high performance insulation PIR (Polyurethane rigid foam). Finally, there is the brick cladding leaving first a 10mm air cavity to increase thermal insulation and prevent moisture to penetrate to the inside of the building. Where the structure meets the upper part of windows or any other openings, then a steel profile is attached to the brick cladding to prevent thermal bridges, support the system and expel the water. The projection of this profile has the shape and the use of a gutter to lead the water to the sides, preventing it from falling in front of the window or leaking to the interior space. This element is attached to the cladding and allows a small distance from the window parts, in order to permit moisture, possibly produced inside, escape to the outside. On the bottom part of the window, a planter can be adjusted above the system. The planter gets attached to the plastic strips and is held by a steel bracket transferring the load to the structure. Water drained from the planter drops on the frog of the protruding brick. Another idea could be to place a small water reservoir instead of a planter using the same assembling coherent. This could be useful in case of larger façade surfaces that would require more water supply. The lintels of the entrances are solved similar to the upper window parts (figure 49) and the insulation remains continuous so that there are no thermal bridges.

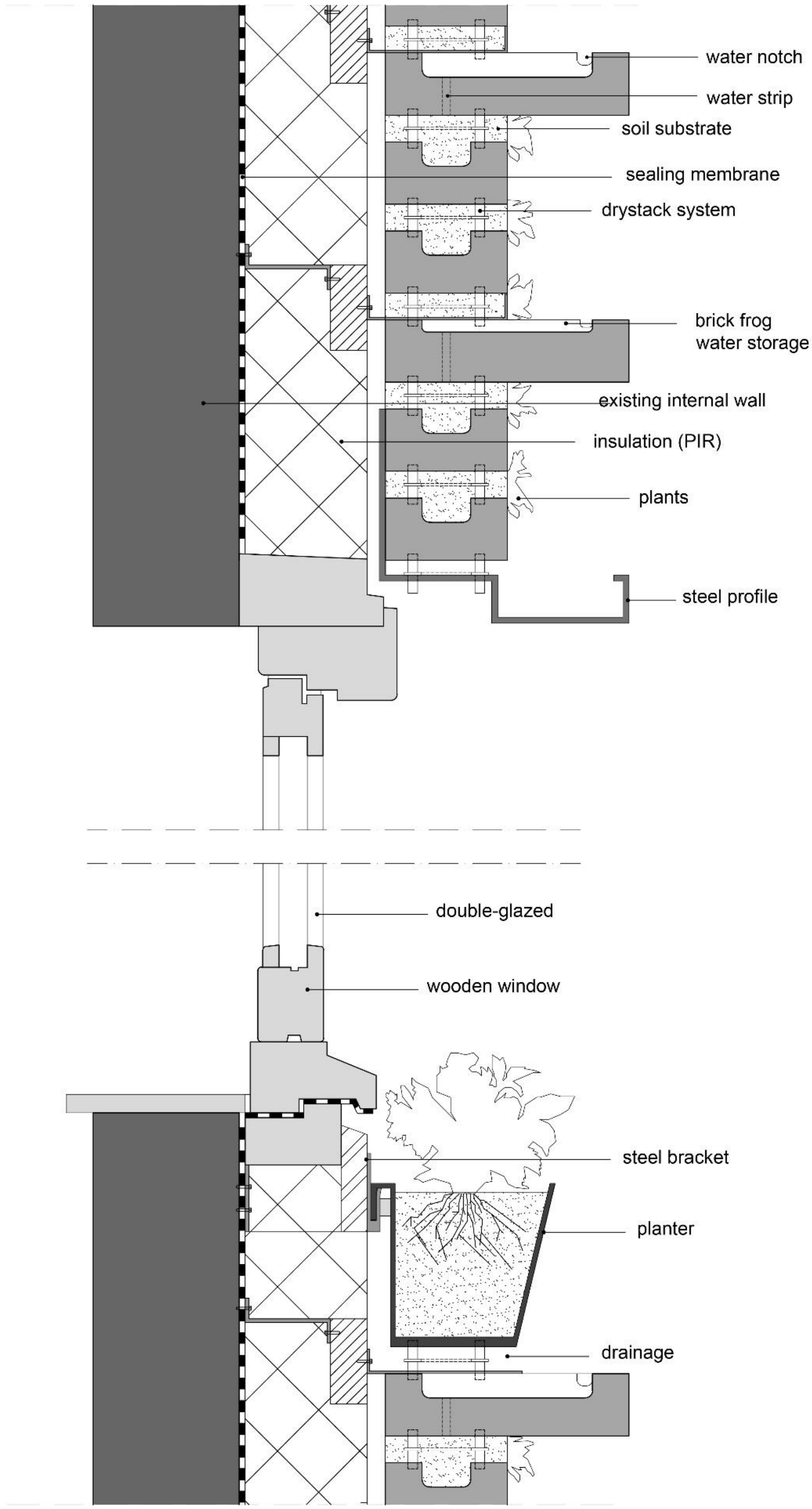


Figure 48: Section detail, components (own work)

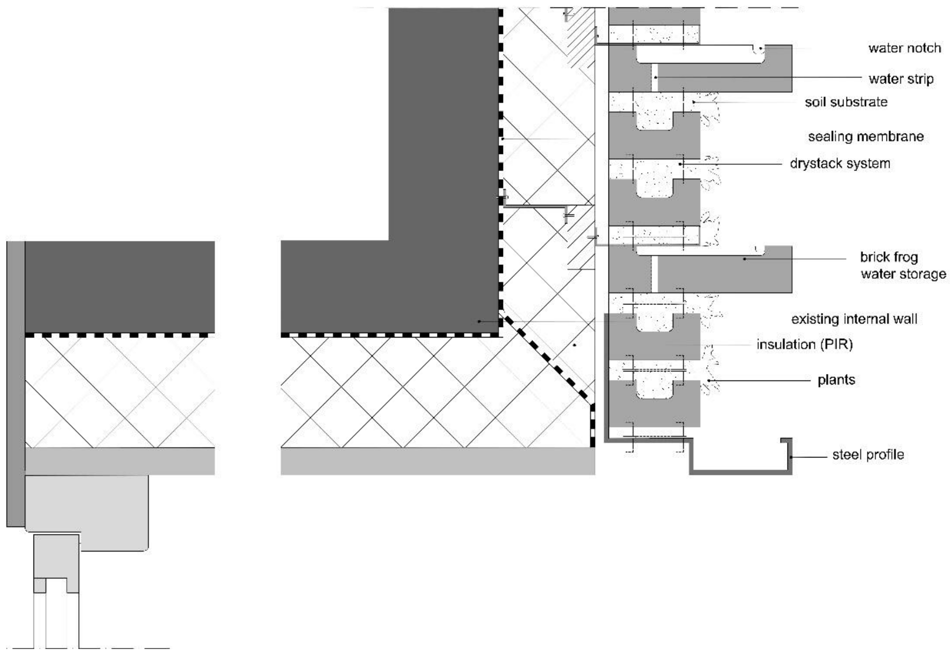


Figure 49: lintel detail (own work)

The reservoir, on top of the system (figure 50), gathers the water and then through a small orifice the water exits and flows towards the first frog. There are multiple small openings parallel to the frogs of the first line of protruding bricks on top. The assembling of the reservoir resembles the stacking logic of the system and is attached with a clicking mechanism into a steel bracket connected to the structure inside.

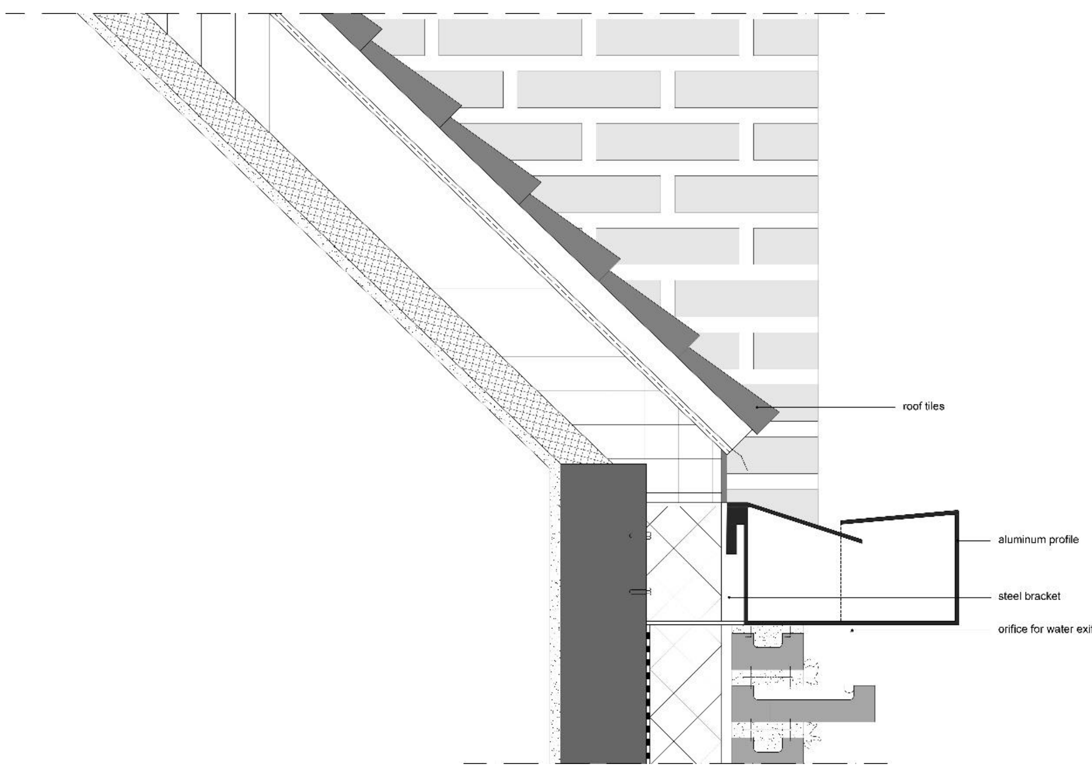


Figure 50: water reservoir detail (own work)

The water system can be better understood by looking at the horizontal sections (figure 51, 52, 53). Water is stored in the reservoir and inside the frogs, from where it then passes to the soil with the through hole, which is placed on the bottom of the frog. On the projection of the bricks, the notches help the water, coming from the water reservoir or by rain, to move downwards gradually and fill all of the frogs.

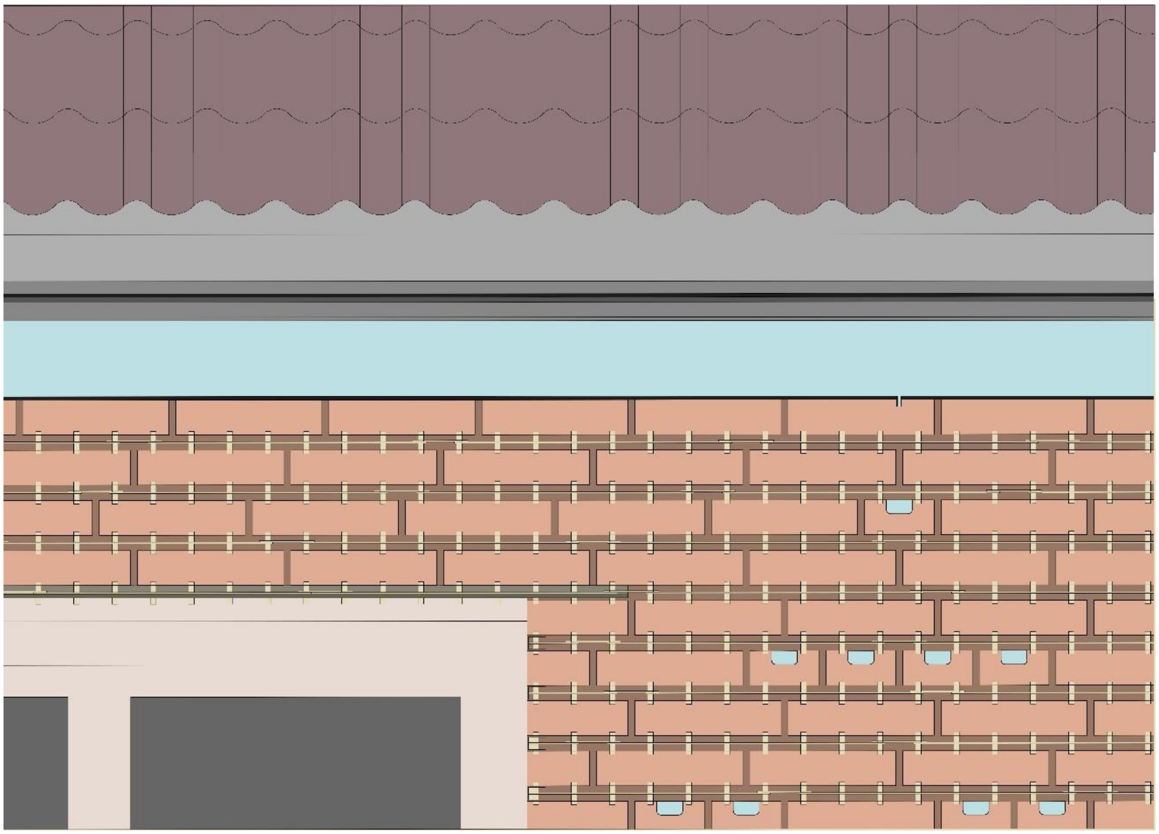
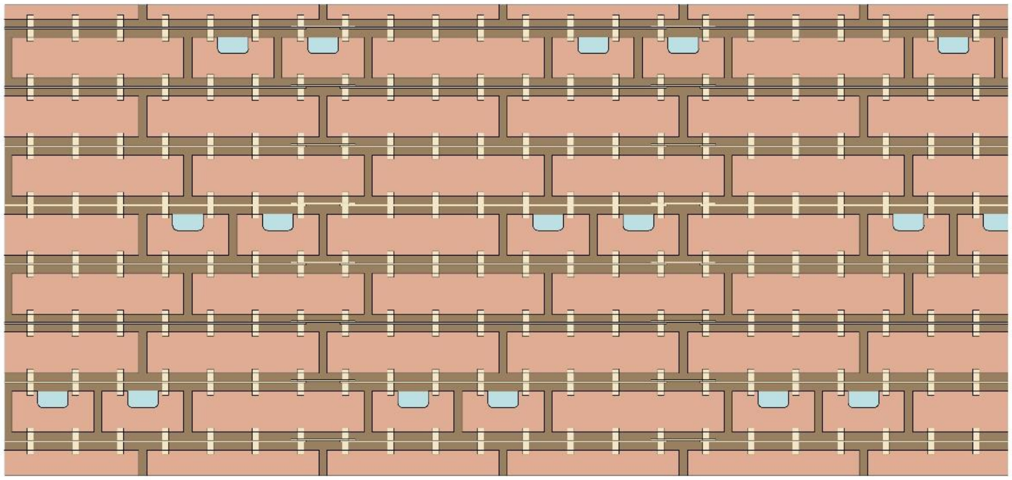


Figure 51: Horizontal section on top of the façade (own work)



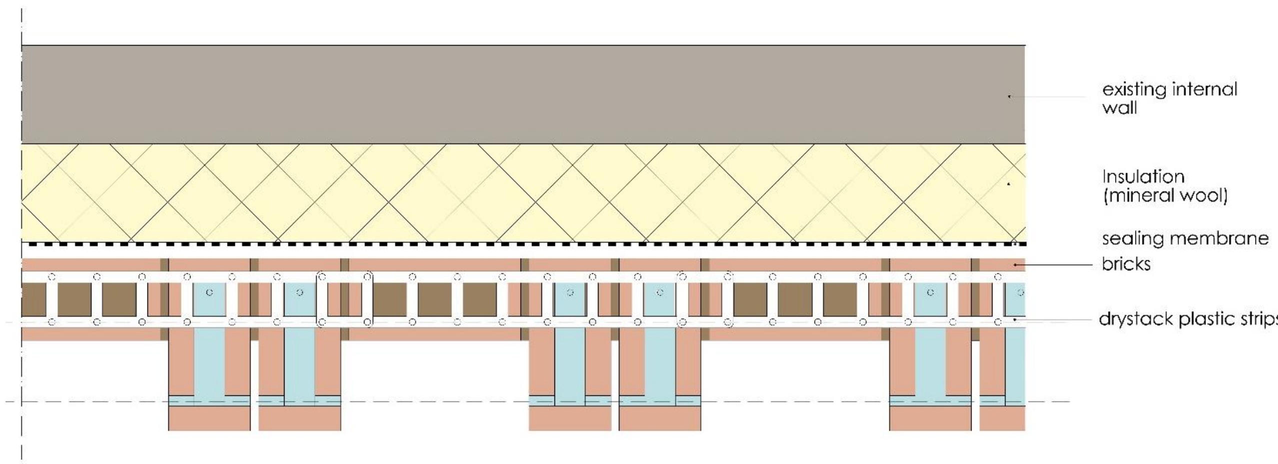


Figure 52: Horizontal section and plan (own work)

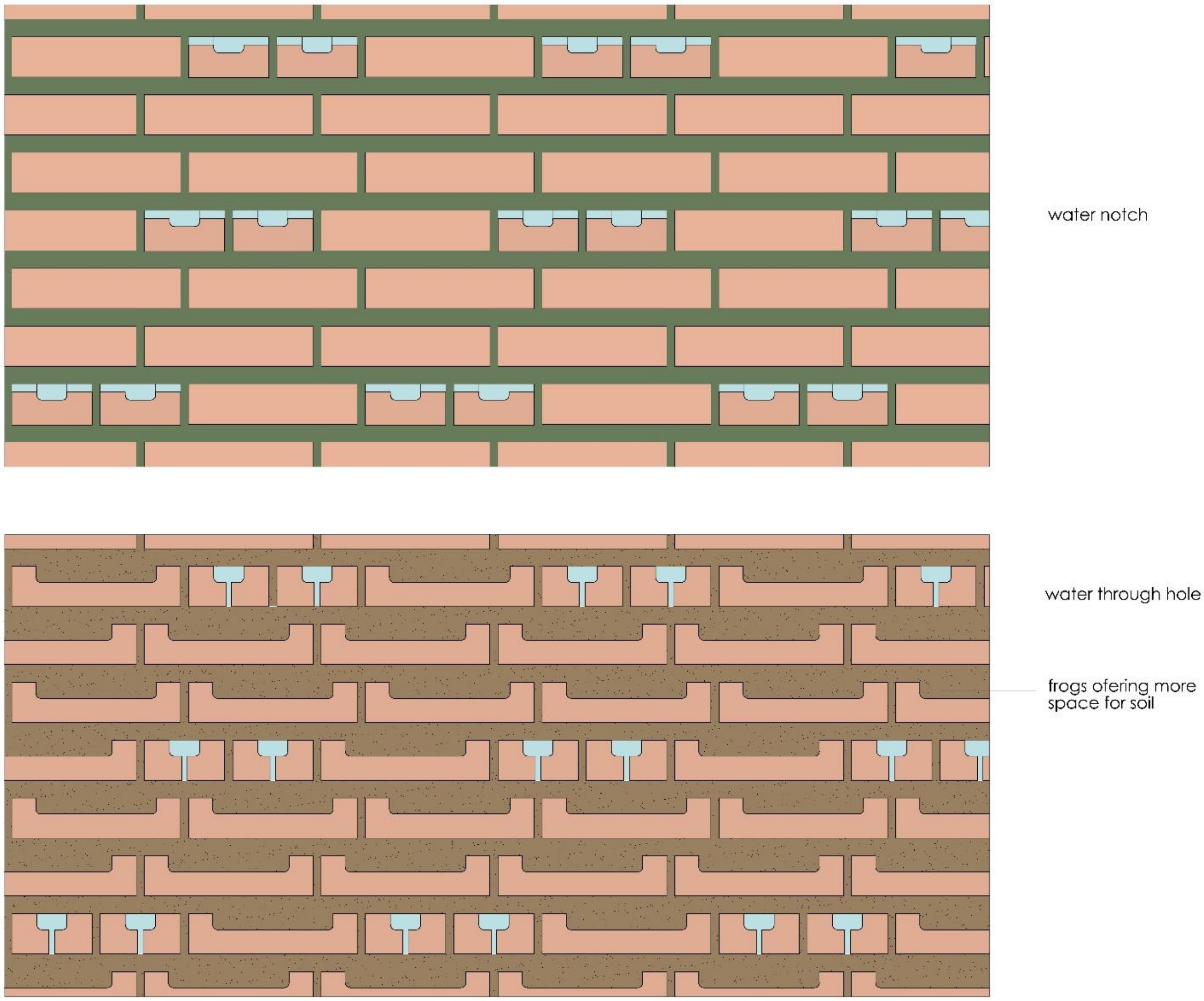


Figure 53: Horizontal sections, one cutting the protruding bricks and the other cutting the soil (own work)

Finally, in the façade drawings (figure 54, 55), one part of the building is designed according to the new system and also the watering system is presented as a whole. The bricks are placed according to the system requirements and some bricks on corners require cutting to fit the dimensions of the façade. The pattern offers an interesting view and at the same time it works efficiently to provide all of the façade surface with water. The water reservoirs are placed on top and water exits from their openings, which is then controlled to spread gradually and carefully not to flow inside any openings. At the bottom of the façade, there is drainage space in order to help water, which is not absorbed by the soil, to escape. Otherwise there would be a danger of oversaturating the lower parts of the wall.

Figure 54: Facade of the building (own work)

Figure 55: Watering system of the façade (own work)

8. Materials and products

It is very important to define the requirements of the basic elements that constitute the system. These are the bricks, the drystack strips, the plants and the soil substrate. Irrigation is also crucial and requires designing.

8.1 Bricks

First of all, the brick requirements are the following:

- High water absorption (porous)
- Frost resistant (durable)
- Sufficient mechanical strength
- Perforations or frog
- Variation of colours

The selected brick needs to be porous. Water absorption levels are important because moisture stored in bricks can be used by the plants for their growth.

Durability is a major requirement for brick as a construction material because deterioration of bricks may seriously affect the stability of the structure. Main factors leading to deterioration of brick properties are the crystallization of salt and the cycles of freezing and thawing (Netinger I. et al. 2014). When water gets inside of bricks during winter it has the potential to freeze, causing it to expand. Pressure from this expansion, especially when it happens over and over, leads to cracking and crumbling masonry.

The porosity and distribution of pore sizes constitutes a critical factor for the durability of construction materials. During production of bricks, the objective is to obtain the smallest proportion of medium size pores, and the maximum proportion of large pores. Pores larger than 1 mm (large pores) are easily filled with and emptied of water. That is why they improve the durability of bricks. Small pores (less than 0.1 mm in size) do not significantly affect the brick's resistance to freezing/thawing cycles as water freezes in such pores only at very low temperatures. However, during formation of ice, water may move from small pores toward large pores and create ice mass. Medium size pores (from 0.1 mm to 1 mm) are most susceptible to the freezing/thawing action (Netinger I. et al. 2014).

At the same time mechanical strength is also important. A stress is generated in material during conversion of water into ice, and the material uses its own tensile strength to withstand such stress. A high tensile strength of material also implies a high compressive strength, and so it can be concluded that the greater the compressive strength of material, the higher its resistance will be to freezing/thawing cycles. As the compressive strength is inversely proportional to the total porosity of material, a low strength brick will also be characterized by greater porosity, which will make it susceptible to damage during the freezing/ thawing cycles.

Perforations or a frog can help storing water or soil, supporting the plant growth. A variation of colours is not a functional requirement but it adds on the aesthetics of the façade by making the texture more interesting and vivid, while it can also highlight the design pattern.

Considering brick selection in terms of the production process, soft mud molded bricks and extruded bricks are compared. Both types have the same physical makeup and do not differ in quality or weather ability. They both vary also in sizes, colors, textures and shapes.

The soft mud molded bricks constitute the most traditional method of brick manufacturing, which includes sand struck molded brick, and handmade sanded brick. Sand struck molded brick can usually be identified by the presence of sand on five of its six surfaces. Sand struck brick typically also have an indentation (or frog) on one bed. As a rule, sand struck molded brick also tend to be more irregular in size and texture than extruded brick, which is considered a desirable feature. Handmade sanded brick is crafted one by one by hand and then fired with coal to provide the colors and textures identical to those seen hundreds of years ago. Hand molding creates distinctive folds, finger marks, and other surface irregularities which make each handmade brick unique.

The more modern and popular method of brick manufacturing is stiff mud extrusion. Extruded brick is produced when low moisture clay is extruded under pressure through a die to produce the distinct brick shape. They tend to be more regular in size and texture than sand molded or handmade brick.

The soft mud molded bricks are generally made with lean clay mixtures (i.e. low clay content) with generally high water content, in order to facilitate the shaping process; this results in a quite high porosity of the bricks. In the case of extruded bricks, that generally fatter clay mixtures are used, often in combination with a vacuum pump in the extruder; this leads to brick with a lower porosity (Lubelli, B. et al. 2020).

These two types are compared in the experimental research "Influence of brick and mortar properties on bioreceptivity of masonry" and soft mud molded brick is proven to have higher water absorption, meeting the requirements of this project better, although the mechanical strength of extruded bricks is considerably higher.

The final product chosen is brick 2 used in the experimental research "Influence of brick and mortar properties on bioreceptivity of masonry". Its name is Wienenrberger Terca Beerse – Basia Spaans, its natural dimensions are 210x100x50mm, the production process is soft mud molded and it also consists of a frog.

Figure 56: Brick "Wienenrberger Terca Beerse – Basia Spaans"

8.2. Drystack plastic strips

The plastic elements in between the bricks are responsible for the stability and interconnection of the system. According to the company product information, there are four different plastic elements, each having a specific use.

The first one is the DS Layer, which provides the connection between the bricks. This specially developed plastic strip with studs has been tested for fire and pressure resistance. To achieve the correct dimensions of the construction, the DS Layer can easily be cut to size.

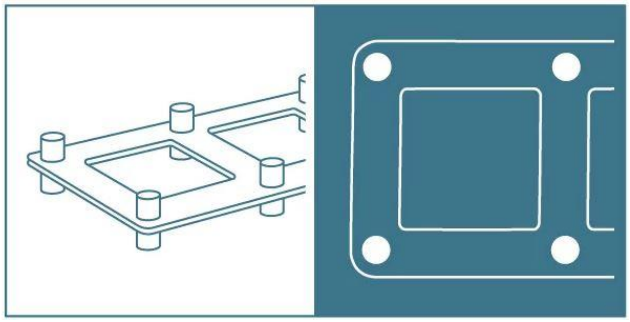


Figure 57 DS Layer drawings (Drystack BV < https://drystack.nl/>)

The second is the DS Bridge ensuring the exact horizontal alignment between the layers. It is always applied to the anchor layer to create a horizontal line load and additional reinforcement of the structure. It is also used at the corners for making the corner square.

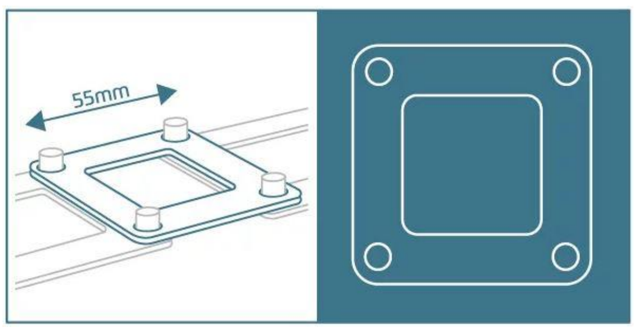


Figure 58: DS Bridge drawings (Drystack BV < https://drystack.nl/>)

Then there is the DS Stand providing extra reinforcement between the brick layers. This plastic strip is vertically linked to the DS Layers and it secures the vertical pulling force.

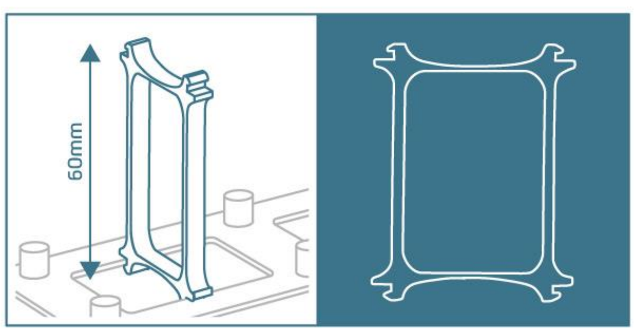


Figure 59: DS Stand drawings (Drystack BV < https://drystack.nl/>)

The last one is the DS Stopper used with the first brick layer and the last brick layer, where there is a transition from brick to other material. The DS Stopper remains in place due to the pulling force of the DS Stand.

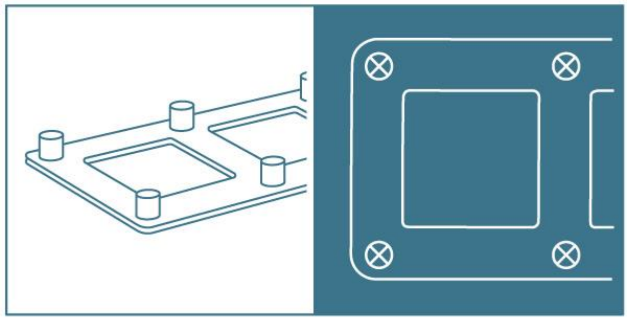


Figure 60: DS Stopper drawings (Drystack BV < https://drystack.nl/>)

8.3. Plants

In order to select the plants that could grow efficiently and without damaging the wall, certain factors need to be taken into account.

- Climate zone
- Sunlight requirements
- Low water requirements
- Low maintenance
- Small roots length
- Groundcover
- Herbaceous
- Evergreen
- Colorful

First of all, climate conditions are crucial and plants need to be selected according to their light and temperature requirements. According to the Plant Hardiness Zone Map, it is clear which plants are most likely to thrive at a geographical location.

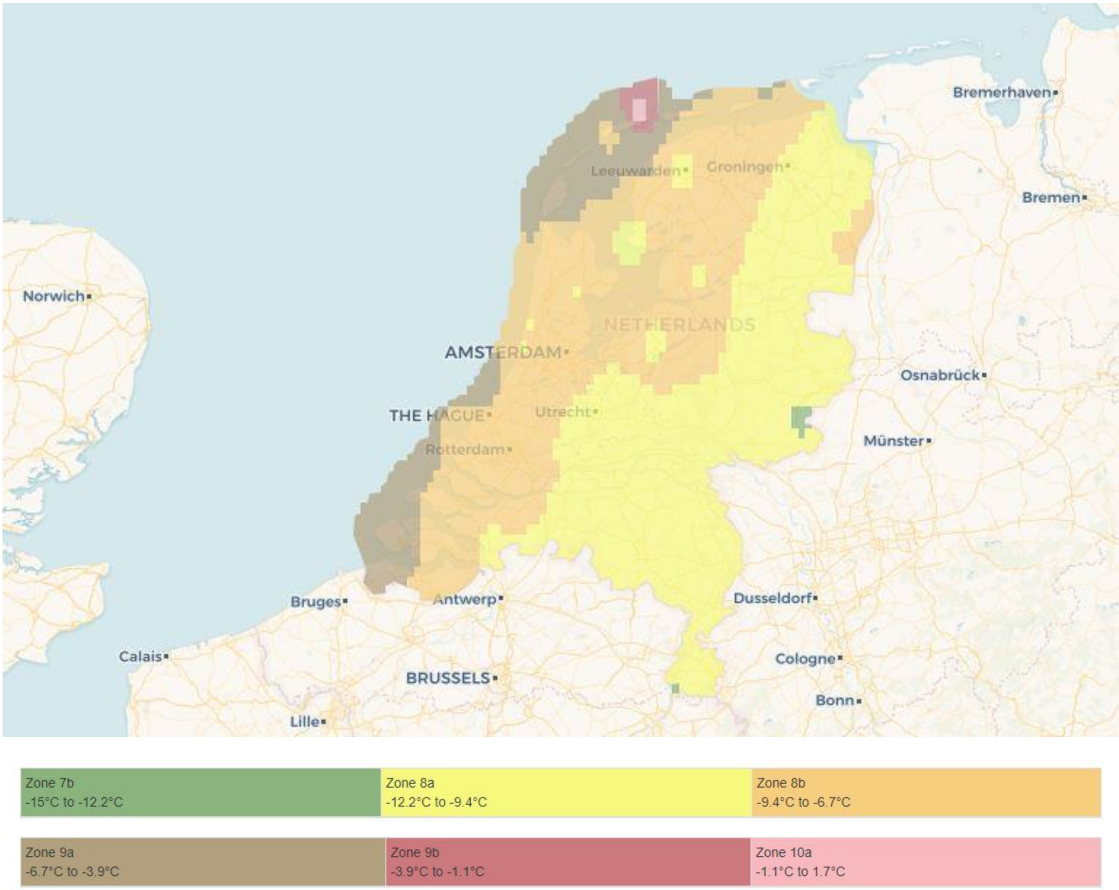


Figure 61: Plant Hardiness Zone Map (QFB Gardening, < https://www.qfbgardening.nl/hardheidszones>)

Choosing plants with low sunlight requirements is essential for a country like the Netherlands and also for the orientation of a building, considering that north facades receive less light than south facades.

Water requirements is another key aspect for choosing the right plants. It is better to grow plants with low water needs, which can survive dry periods. It is also preferable to choose plants which can grow on a wall. As a result, a simple, low cost and easily maintained irrigation system is needed. Apart from the irrigation system, the wall materials need to secure moisture for the proper plant growth. Succulent plants with thick stems and leaves to store water would be an option for drier climates, but not for the Netherlands. Drought tolerant plants in wet climates cannot store much water in their tissues, so they need a minimum moisture content in the substrate.

The growing conditions of plants are also important because vertical greenery does not offer the same freedom and flexibility that horizontal ground does. Gravity plays an important role and plants that tend to grow vertically are hard to cover much of a vertical surface. On the contrary, groundcover plants tend to spread horizontally and thus they could cover efficiently a vertical surface.

Maintenance of plants is also crucial and needs to be very well scheduled to ensure their prosperous growth. Vertical greenery is sometimes difficult to be maintained because some plants may be inaccessible. In that case, the use of a boom lift or other machines can be helpful. Nevertheless, it is wiser to choose plants with low maintenance requirements so that any process is reduced to minimum during the year, thus reducing the cost.

Additionally, the size of the plants plays an important role when growing on vertical wall surfaces. Small plants are more manageable and they have shallow roots, thus not requiring a lot of soil volume for their growth. Moreover, the shorter the roots, the lower the risk of damaging the wall.

Herbaceous plants are very common for vertical gardens and more suitable than woody ones because they are more flexible in the way they grow downwards and they have soft, green stems.

Last but not least, evergreen and colorful plants are preferred in order to offer a more attractive result, while keeping their leaves throughout the whole year means that they also keep all their valuable characteristics (cooling properties, noise reduction etc.).

Table 1: Plant species and their characteristics

Plant species	zone	vertical growth range (m)	horizontal growth range (m)	sun	water need	maintenance	leaf	Ideal PH range
Asplenium trichomanes	5 to 8	0.1 to 0.2	0.23 to 0.3	Part shade to full shade	medium	low	evergreen	
Asplenium scolopendrium	5 to 9	0.3 to 0.46	0.3 to 0.46	Part shade to full shade	medium	low	evergreen	
Chaenorhinum origanifolium	minimum 5	average 0.4		full sun	low	medium		
Corydalis cheilanthifolia	5 to 7	0.3 to 0.46	0.3 to 0.46	Part shade to full shade	medium	low		
Pseudofumaria alba	5 to 7	0.3 to 0.6	0.3 to 0.6	Part shade to full shade	medium	medium		6.1 to 7.8
Campanula portenschlagiana	4 to 6	0.07 to 0.15	0.15 to 0.3	Full sun to part shade	medium	low	colorful	6.6 to 7.5
Trachelium caeruleum	9 to 13	up to 1.2	up to 0.3 m	full sun	medium	low	colorful in summer	
Sedum album	3 to 8	0.07 to 0.15	0.15 to 0.45	full sun	dry to medium	low	evergreen	
Sedum rupestre 'Angelina'	5 to 8	0.07 to 0.15	0.3 to 0.6	full sun	dry to medium	low	colorful	
Erinus alpinus	4 to 7	0.05 to 0.07	0.05 to 0.07	full sun to part shade	low	low	semi-evergreen	
Aurinia saxatilis	4 to 7	0.15 to 0.3	0.3 to 0.45	full sun	dry	medium		
Cymbalaria muralis	5 to 8	0.07 to 0.15	0.3 to 0.45	Part shade to full shade	medium	low		5.5 to 7.2
Antirrhinum majus	7 to 10	0.3 to 0.9	0.15 to 0.3	full sun	medium	medium		
Erigeron karvinskianus	6 to 9	0.3 to 0.6	0.8 to 1.5	full sun	low	low		
Erysimum cheiri	7 to 9	0.15 to 0.6	0.15 to 0.45	full sun to part shade	dry to medium	low		6.5 to 7.5
Asplenium ruta-muraria	5 to 9	0.05 to 0.15	up to 1.2	sun to part shade	dry to medium	low		
Asplenium adiantum nigrum	5 to 9	average 0.2		part to full shade	medium	medium		
Parietaria Judaica	minimum 5	average 0.6		full sun to part shade	medium	low		around 7
Dryopteris filix-mas	4 to 8	0.6 to 0.9	0.6 to 0.9	Part shade to full shade	medium	low		4.5 to 8
Dryopteris carthusiana	3 to 8	0.6 to 0.9	0.6 to 0.9	Part shade to full shade	medium	low		
Polystichum polyblepharum	5 to 8	0.45 to 0.6	0.45 to 0.6	Part shade to full shade	medium	low	evergreen	

Table 1 indicates certain plants researched and chosen according to those requirements. Their images are given in Appendix A. Among those plant species, the ones underlined by pink color are even more preferred and the six marked in yellow make the final selection. After discussing with Edwin Dijkhuis, responsible for the plants in the project of Breda, these ones were proven to be the most suitable for this project. They meet all the requirements and most of them have already been tested in the project “Development of green quay walls in Houthaven”.

Figure 62: Final plant selections

8.4. Soil substrate

A suitable soil substrate needs to be selected for the best wall facade construction and plant growth. The main soil requirements are listed below:

- Natural soil substrate
- High permeability
- pH 6 to 7.5
- Light weight
- Capillarity

First of all, it is crucial to define and explain those parameters.

A **natural soil substrate** consists of nature based materials with a minimum environmental footprint.

Permeability: A soil mass is composed by small soil particles which are called the soil grains. They are composed in a way that some amount of empty space is left between them, the voids. These voids are interconnected and form a highly complex network of irregular tube like structure. When water is subjected to a potential[2] difference in the soil, it flows through

[2] Soil-water potential is a measure of the potential energy per unit mass, volume, or weight of soil water, compared with that of pure, free water (Y. Garc and D. Cruz 2016)

these voids form high potential to low potential. The surface of the soil particles offers a resistance to the flow of water. The more irregular and narrower the voids, the greater the resistance posed to the water flowing, while the more open and regular the voids, the greater is the ease that water flows through the soil. This property of the soil which permits the water or any liquid to flow through it, through its voids, is called permeability. The larger the soil particles are, the larger the volume of voids and the better the connectivity of the voids. Thus the higher will be the flow of water which means that soil has high permeability (K. R. Arora 2020). However, size distribution is also a factor influencing permeability. Even if the particles are large, there is a possibility of small particles filling the gaps in between, thus reducing the permeability.

Gravel soils are most permeable, while clay soils are least permeable. Clay soils have high void ratio and high volume of voids because of their flocculated structure. However, soil particles are very small and the voids are poorly connected to each other and they form irregular tubes. Thus, even after having large amount of voids, clay soils are less permeable. When a soil has extremely low permeability, it is called impervious soil. Permeability is highly affecting the water flow and it is represented by the permeability coefficient or hydraulic conductivity K, a value referring usually to saturated soil.

Table 2: Representative values for Hydraulic Conductivity of soils (Structx)

Description	k(m/s)
Sand	1.76E-04
Loamy	1.56E-04
Sandy loam	3.45E-05
Silty loam	7.19E-06
Loamy	6.94E-06
Sandy clayey loam	6.32E-06
Silty clayey loam	1.70E-06
Clay loam	2.45E-06
Sandy clayey loam	2.17E-06
Silty clay	1.02E-06
Clay	1.28E-06

Table 3: Typical permeability classes (Structx)

permeability classes	k (m/s)	
	min	max
Permeable	2.00E-07	2.00E-01
Semi-permeable	1.00E-11	1.00E-05
Impermeable	1.00E-11	5.00E-07

At this point it is crucial to define two variables determining permeability. Soil porosity (1) or pore space is the portion of the soil's volume that is not occupied by solid material. This amount of space is available for water to flow. The porosity of a soil depends on several factors, including packing density, the breadth of the particle size distribution, the shape of particles, and cementing (Nimmo, J. R. 2013). Soil porosity can be fairly defined and measured while pore size (2) definition or measurement is hard and not obvious. Pore size is of great importance for quantifying soil structure, while it has also a major practical role in the prediction of hydraulic properties. The size distribution of pores and fluid conduits is useful for predicting hydraulic conductivity K, as well as for water retention. Porosity depends on the size, shape, and mixture of grains and particles that compose soil. For instance, small particles such as clays are able to compact more closely together, reducing the amount of porosity. However, larger particles such as sand and gravel will have more spaces available between them. Round particles compacted together will have more spaces than elongated grains that stack more tightly. Particles of uniform size (well sorted) will also have more pore space available than grains of varying sizes (poorly sorted) because small particles can fill in the spaces between the larger grains (Nimmo, J. R. 2013).

Soil pH is a measure of the acidity or basicity (alkalinity) of a soil. Soil pH is considered a master variable in soils as it affects many chemical processes. It specifically affects plant nutrient availability (Colorado, I. 2020). The optimum pH range for most plants is between 5.5 and 7.8 and soils are classified according to their pH range, as indicated by the USDA[3].

Table 4: Classification of soil pH ranges according to the USDA

Denomination	pH range
Ultra-acidic	<3.5
Extremely acidic	3.5-4.5
Very strongly acidic	4.5-5.0
Strongly acidic	5.1-5.5
Moderately acidic	5.6-6.0
Slightly acidic	6.1-6.5
Neutral	6.6-7.3
Slightly alkaline	7.4-7.8
Moderately alkaline	7.9-8.4
Strongly alkaline	8.5-9.0
Very strongly alkaline	>9.0

The most suitable soil pH for most plants is in one of the four categories underlined by green in table 4.

[3] United States Department of Agriculture

The selected soil substrate needs to be relatively **lightweight** so that the total façade system is not overloaded. Making a light construction offers a sustainable solution, in terms of easier transportation and handling of the materials.

Capillarity is the ability of a liquid to flow inside narrow spaces against gravity and without the assistance of external forces. In order to understand this effect in soils, the voids between the soil grains can be compared with a small diameter glass tube, because these voids are interconnected and form a channel of tube like structure. The smaller the diameter of the tube, the higher will be the maximum height which can be reached by water by capillary transport. Capillarity, which is the mechanism governing rising damp in a wall, is a consequence of surface tension. Because of the attraction between the liquid and the capillary walls, the liquid rises in a capillary and a meniscus is formed (Lubelli, B. A. A. 2006).

Capillary Rise:

$$hc = \frac{C}{e \times D10}, \text{ (E library 2020)}$$

Where C is the empirical constant[4] and D10 the effective diameter.

The calculated height is valid only in theory, since in reality the maximum height is limited by irregularity present in the pore section (Lubelli, B. A. A. 2006).

In soil, if grain size decreases, then also the pore size decreases. Thus, the channels composed by the voids are narrow, meaning the capillary rise increases. These can be called fine grained soils. Coarse grained soils consist of larger voids and the capillary rise is small. However, the moisture transport in a material with fine pores is slower than in a material with coarse pores. This means that the quantity of water transported by capillarity in a fine porous material in a defined time period will be limited (Lubelli, B). Additionally, pores with radius < 0.1 μm are practically ineffective in absorbing water and do not contribute to capillary transport, because they are too small and absorption becomes extremely slow. (Lubelli, B. A. A. 2006).

Capillary rise is dependent on pore size and not on grain size. It is also important to take into account that a soil mass can have different pore size distributions in different deposits of the same soil. This can cause different capillary rise. In reality, voids are not like capillary tubes, they are irregular in shape and size and they are not necessarily continuous and inter-connected or vertical. This is because they are created by a random assembling of grain soils.

Taking into account the above information, it can be understood that high capillarity means low permeability. High permeability requires large voids to support an easier and faster water flow. Nevertheless, coarse grained soils with very high permeability may cause the water flow too fast and thus not being retained by the soil. A fast downwards water flow may lead to erosion and collapse of the substrate. Water will also flow downwards due to gravity and for the current project horizontal movement of the water is also required, in order to moisten the maximum of the substrate.

[4] A physical constant that may be measured indirectly and then calculated. Most of the time there is not much scientific rationalization (except perhaps dimensional analysis), so an empirical constant is sometimes just a fudge factor.

According to the needs of each project, a soil can be selected taking into account its characteristics and the requirements of the project. For the current one, the soil needs to have quite high permeability (k value), so that water can flow efficiently through the soil. At the same time capillarity is also required, so that some water moves upwards and horizontally and not only downwards.

The first two candidate soil substrates examined are BVB and ACCAP 7120. According to their datasheets given on the Appendix B they seem to have very similar composition and they are both favorable for quay walls. However, they could not make a final choice because of supplying difficulties from the producers. Therefore, another product had to be found.

Then, the "Tree Ground Solutions" (TGS) company was contacted, which was found through the project report "Development of green quay walls in Houthaven Amsterdam". For that project they used and tested the "Capillary sand TGS + fiber" substrate. After discussing with the producer the requirements of the current thesis project, two other substrates were also proposed, the "TGS upper light" and the "TGS lower light". Their properties are analyzed and compared, seeking for the best option (table 7).

The proportion (relative percentages) of sand, silt and clay sized particles that make up the mineral fraction of the soil is defined by the term soil texture (Bridges, M. 2014). For example, light soil refers to a soil with more sand than clay, while heavy soils are made up largely of clay. Texture is important because it influences the amount of water the soil can hold, the rate of water movement through the soil and how workable and fertile the soil is (Bridges, M. 2014). The mineral fraction or mineral matter refers to the soil particles that differ in size and are labeled according to it, as shown on table 5.

Table5: Diameter limits of soil particles according to USDA

Name of soil particle	Diameter limits (mm)
Clay	< 0.002
Silt	0.002-0.05
Very fine sand	0.05-0.10
Fine sand	0.10-0.25
Medium sand	0.25-0.50
Coarse sand	0.50-1.00
Very coarse sand	1.00-2.00

Sand has the largest range of diameter. The bigger the soil particles, the larger the pore spaces, which improve aeration and permeability. Soils with a high percentage of sand are generally well drained.

Silt constitutes the mid-size soil particle and it secures good water-holding capacity and good fertility characteristics.

Clay is the smallest soil particle, thus creating very small pore spaces and restricts water flow and aeration. However, it is important for plant growth because it has the ability of holding nutrients and water.

Table6: Diameter limits of soil particles according to USDA classification

Diameter limits (USDA classification)						
Soil particle	Min (mm)	Max (mm)	Min (µm)	Max (µm)	Capillarity	Permeability
Clay	0	0.002	0	2	Medium	Low
Silt	0.002	0.05	2	50	High	Low - Medium
Very fine sand	0.05	0.1	50	100	Medium	High
Fine sand	0.1	0.25	100	250	Medium	High
Medium sand	0.25	0.5	250	500	Low	Very High
Coarse sand	0.5	1	500	1000	Low	Very High
Very coarse sand	1	2	1000	2000	Low	Very High

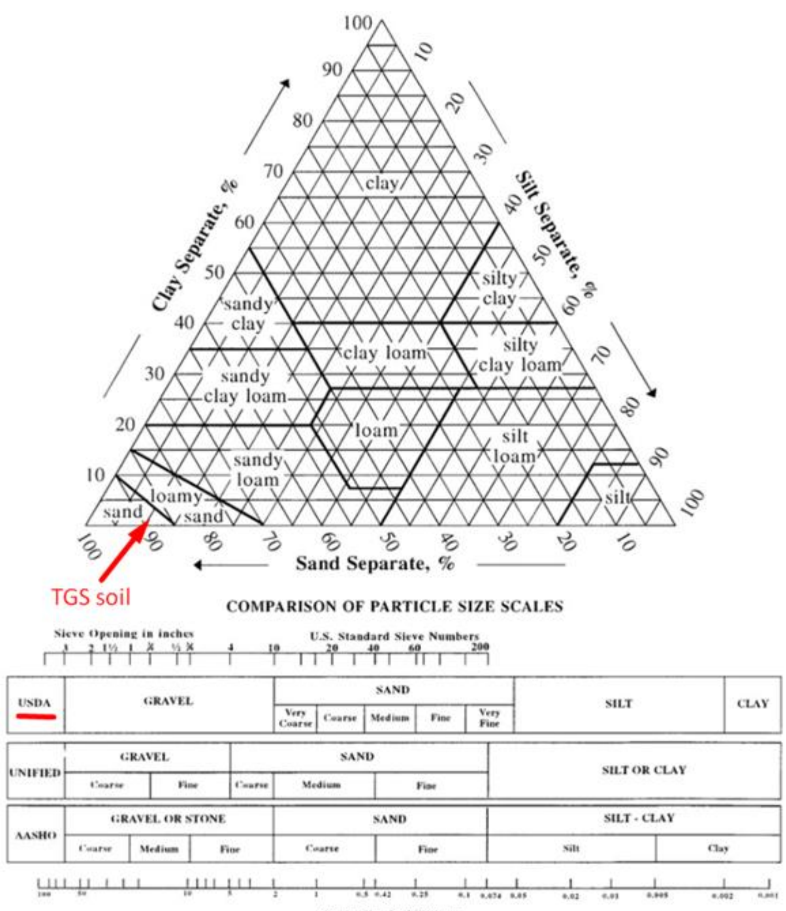


Figure 63: Comparison of particle size scales/ range of the TGS soil (Wikiwand <https://www.wikiwand.com/en/Soil_texture>)

Figure 63 indicates a soil textural triangle, a diagram which shows how each of the 12 soil textures is classified based on the percent of sand, silt, and clay in each. All three TGS substrates have very high percentage of sand and low percentage of silt and clay. Thus, all three are classified as Sandy soils.

The following table indicates the different weight percentages of soil particles that constitute the three TGS soil substrates.

Table 7: soil particles of the three soil substrates given in weight percentages (provided in the technical sheets of the TGS Company)

	weight percentage		
	Capillary sand TGS + fiber	Upper substrate light 30/4/21	Lower substrate light 30/4/21
Soil particles	%	%	%
Clay	0.8	0.5	0.4
Silt	12	2.4	2.3
Very fine sand	14	7.2	7.1
Fine sand	63	41	39.9
Medium sand	7	16	15.9
Coarse sand	2	14.5	16
Very coarse sand	1	18.4	18.2
Total sand	87	97.1	97.1

According to these data, the "Capillary sand TGS + fiber" has higher capillarity and less permeability than the other two. It has the highest percentage of silt, which increases the capillarity and the water-holding capacity. Clay percentage is also higher, thus making the pore spaces smaller and reducing the ability of water to flow and drain. Additionally, this substrate is also the heaviest one because it has the smallest percentage of sand. Considering the requirements of the project, the TGS capillary sand substrate cannot make an optimal solution.

The two other soil substrates are further compared to understand which one can make the best option. In table 8 their composition is given in volume percentages of the different included substances.

Table8: Soil consistency given in volume percentage

	volume percentage	
	Upper substrate light OM 8%	Lower substrate light OM 2%
soil consistency	%	%
sand	25	39
bims (pumice)	25	39
grower's potting soil RAG	49	21
lava fiber	1	1
Total	100	100

The weight of the substrate is determined by the sand and the grower's potting soil RAG. The weight of the rest substrate materials (pumice and fiber) is negligible.

Bim (in Dutch) or pumice is a natural product, a type of extrusive volcanic rock, produced when lava with a very high content of water and gases is discharged from a volcano (Caiza, M. et al. 2018). It is very soft and lightweight, while it also has a great water absorbing capacity.

The grower's potting soil RAG is the soil material of the substrate. This defines also the organic matter (OM) percentage of the substrate, since the added sand, pumice and fiber have 0% OM. The soil organic matter (SOM) represents the organic constituents in the soil, including undecayed plant and animal tissues, their partial decomposition products, and the soil biomass (Weber, J. 2015). SOM provides numerous benefits to the physical and chemical properties of soil. It has a nutritional function because it works as a source of nitrogen (N) and phosphorous (P) for plant growth and also a biological function by affecting the activities of micro flora and micro faunal organisms. Moreover, it has a physical and physic-chemical function by promoting good soil structure, thereby improving tilt, aeration and retention of moisture and increasing buffering and exchange capacity of soils (Weber, J. 2015).

Organic matter is very important for soil structure, because it holds individual mineral particles together in clusters. A better structure allows water to drain through soil and allows oxygen and carbon dioxide to move freely between spaces within the soil and the air above.

Table 9: Organic matter classification

Organic matter (%)	Criteria
<1.00	Very Low
1.00-2.00	Low
2.10-4.20	Moderate
4.30-6.00	High
>6.00	Very High

The lava fiber added to the soil substrate provides similar properties with the pumice but it is in the form of fibers and not irregular particles like pumice. It is probably only 1% due to high cost.

Regarding their volume percentages, the soil with more sand and pumice is the most lightweight. Larger sand portion can provide also better drainage and thus the TGS lower light substrate is expected to perform better. Both soil substrates are provided by the TGS Company and they are both tested with different experiments to define their actual performance in terms of assembling, water pouring on the façade and water transport inside the soil. These are going to be analyzed and discussed in the Experiment chapter.

8.5 Irrigation

According to the selected plant requirements the plants can survive the dry period with one irrigation per two weeks. Even if they lose their color and flowers, they still survive and will flourish again under the proper climate conditions, mostly during springtime. However, most of the selected plants are evergreen, meaning that they keep their leaves all seasons.

The irrigation takes place with a water reservoir on the top of the façade system. The protruding bricks help the water to spread gradually and equally to the whole wall surface. During the rainy periods, water can go straight to the protruding bricks and the plants. The water reservoir will collect the rain water to use it for dry periods.

A drainage needs to be ensured below the wall façade in order to evacuate any excess of water from the lower part of the wall. Excess of water may keep the substrate saturated for long, which is detrimental provoking to plant roots asphyxia, decay and fungi diseases. Especially in case of a downpour, the excess of water accumulating at the bottom end needs to be quickly removed.

The water volume of the reservoir, located above the 12 m2 of the façade, when filled, is 99 liters (0.099 m3)

It is explained below (8.5.1) that for one irrigation 12 liters are required, which means that the capacity of the reservoir allows for 8 times of watering (8*12=96 liters). As foretold, during dry periods the selected plants may survive with 1 irrigation per two weeks. Thus, the capacity of the reservoir can be sufficient for the whole summer period even if no rainfall occurs which is improbable for the Dutch climate. The dry season or else the season that irrigation may be required is approximately from 15/5 to 15/9, which is 4 months or about 120 days. Then, 1 irrigation/2nd week is 120/15= 8 irrigations in total.

8.5.1 Time and volume of watering

The required amount of water for a specific area of the wall needs to be known in order to control the water provided from the reservoir.

We assume that 1 m2 of soil surface requires 3 liters of water per irrigation. For one part of the wall which is 12 m2, only the 4 m2 are covered by soil. Thus, 3*4= 12 liters of water are needed (0.012 m3) for each irrigation.

The assumption that 3 liters/ m2 are required is based on the fact that drought tolerant plants may need no supplemental water, or need watering only once or twice a month in dry weather. Twice a month is about 8 irrigations during summer months (15/5 to 15/9), totals 3*8 = 24 liters of water, which is equivalent to 24 mm of rain (A rainfall of 1 mm / m2, equals 1 liter of rain water). A rainfall or irrigation of 24 mm is most likely adequate for drought tolerant plants that survive by minimizing all their physiological functions to adapt to low summer rainfall.

It is known that 1 mm of water applied to the surface of a soil will soak soil in more than 1mm depth. Shallower in heavy soils, deeper in sandy soils. Therefore, the highly sandy wall substrate is probably moistened more than 5 mm in depth at every irrigation, meeting easily the shallow roots of the selected plants

The protruding bricks collect the water coming from the reservoir and gradually pass it from one to the other. The volume of one brick frog is 5.6e-5 m3. At this 12 m2 area there are 248 protruding bricks and thus the total frog volume is 248*5.6e-5= 0.0124 m3 (12.4 liters). It is almost equal to the total water required (12 liters) and thus the amount of water spread from the reservoir will fill all of the frogs efficiently.

In order to control the water flow from the reservoir, time control is required. This time can be calculated taking into account the volume of water exiting, the cross-section of the orifice, the velocity, the water flow and the height of the reservoir. Considering that the time is in inverse proportion to the cross-section of the orifice, the radius of the orifice should change according to the different soil areas below the reservoir. If the soil area is larger, then the required amount of water is also higher and if the radius of the opening remains the same, then more time is needed. However, it is better to monitor all the reservoir system to work at the same time for the same duration. Therefore, the radius of the orifice should change according to the soil area that needs to be covered, so that the time for the required water amount exiting remains the same.

The formulas used are the following:

$$t = \frac{V}{Q}$$

$$Q = A \times v$$

$$v = Cv \times (2 \times g \times H)^{\frac{1}{2}}$$

$\frac{1}{2} mv^2 = mgh \Rightarrow v^2 = 2mgh/m \Rightarrow v^2 = 2gh \Rightarrow v = (2 \times g \times h)^{\frac{1}{2}}$

t: total time for water to exit (s)

V: total volume of water exiting (m3)

Q: water flow (m3/s)

v: velocity of water flow (m/s)

Cv[5]: flow coefficient of water=0.97

g: The acceleration of gravity constant ($9.81 m/s^2$)

H: height of the reservoir (m)

[5] Cv coefficient is the number of U.S. gallons per minute of water that will pass through a given orifice area at a pressure drop of 1 PSI (About Cv 2012)

A: the cross-sectional area of the opening and it is calculated as: A=πr^2

Then rewriting and combining the above equations r can be calculated:

$$Q=A\times v = \pi \times r^2 \times v, \qquad t = \frac{V}{Q} = \frac{V}{\pi \times r^2 \times v} \rightarrow \pi \times r^2 \times v = \frac{V}{t} \rightarrow \boldsymbol{r} = \left(\frac{\boldsymbol{V}}{\boldsymbol{\pi \times v \times t}}\right)^{\frac{1}{2}}$$

This way the radius of the orifice for the reservoir can be calculated according to the amount of water needed for each soil area.

Taking, for example, the façade of the building case study, the different radius for some façade parts were calculated.

Figure 64: Water reservoirs supplying different facade areas of the building case study (own work)

Firstly, the façade part, in figure 64, named area 1 has a total of 6 m^2 soil and multiplied with the volume for 1 m^2, the required water volume is calculated 0.018 m^3. Considering that the reservoir opens for 1 minute and that it consists of 3 opening, then the radius of the opening is calculated 0.0025 m. Similarly, area 2 has a total of 4.34 m^2 of soil area and requires 0.013 m^3 of water. Consisting of 2 openings and considering again the 1 minute, then the radius of the orifice is 0.0032 m. Radius for the orifices of area 3 and 4 are similarly calculated, as indicated on table 10.

Table 10: Radius variation for different facade surfaces

	Area (m^2)	Volume (m^3)	openings	radius (mm)
Area 1	6	0.018	3	2.5
Area 2	4.34	0.013	2	3.2
Area 3	4	0.012	3	2.1
Area 4	6.2	0.0186	2	3.8

Consequently, the radius depends on the area of the soil below it and on the amount of the openings, from which the water exits. All of the radius calculated for this building are considerably small and one minute can be enough for all the water to exit and spread towards the façade surface.

8.5.2. Structural load

The system needs to be structurally checked to make sure that it can stand the load subjected by the water reservoir on the top. When the reservoir is full of water its mass is calculated using the formula;

$$m = \rho \times V$$

ρ: water density [kg/m3]= 1000 kg/m3

V: water volume [m3]= 0.99 m3

m= water mass [kg]= 99kg (99 liters reservoir)+ 9 kg (mass of empty reservoir)= 109kg

Considering the dimensions of the reservoir, a thickness of 5mm and acrylic material, a web calculator is used and the weight of the reservoir empty is measured 9 kg.

Then the load is calculated by the formula:

$$W = m \times g = \ 109\ kg\ *\ 9.81 \frac{m}{s^2} = 1069N$$

W= 1069 N, which is the force exerted as a distributed load on the surface below the reservoir. The compressive strength of the reservoir is calculated with the following formula:

$$\sigma = \frac{F}{A}$$

F: The force exerted by the reservoir [N] = F=1069 N

A: the horizontal area of the reservoir [m2] = 0.7128 m2

σ=1499 Pa= 0.001499 MPa

The ultimate compressive strength of mud bricks is 7 MPa and the ultimate compressive strength of Poly Amide (the material of the plastic drystack strips) is around 2MPa. Thus, the stress exerted by the reservoir when it is completely filled with water is below limit and cannot cause the structure to fail.

However, taking into account that the reservoir protrudes, it needs to be checked whether the moment generated by the water reservoir is compensated in the structure. The reservoir is attached to a steel support inside the wall, which is then bolted onto the interior existing wall structure. The cross-section of the screw needs to be defined to ensure the compensation of the moment.

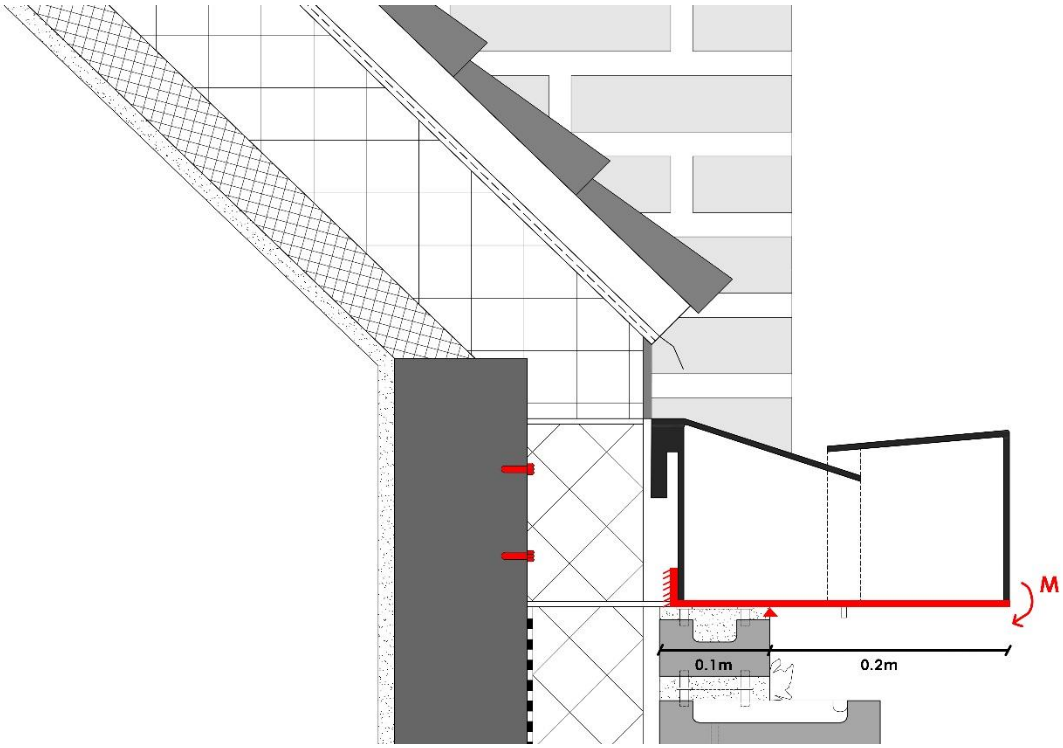


Figure 65: Moment of the water reservoir, drawing detail (own work)

The system can be simplified to a beam in order to find the moment.

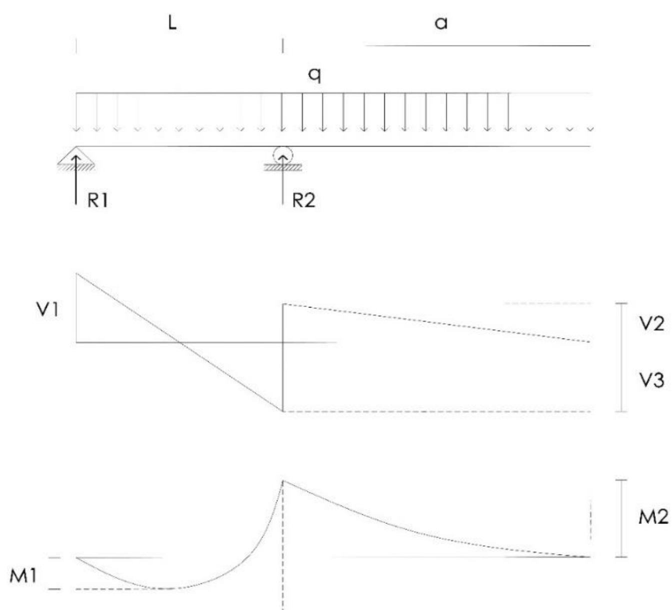


Figure 66: Beam analysis of the reservoir, shear force and moment diagram

First the distributed load is calculated and then the moment using the following formulas:

$$q = \frac{F}{L+a} = \frac{1499 \times 10^{-3}}{0.3} = 4.99\frac{KN}{m}$$

$$M2 = \frac{q \times a^2}{2} = \frac{4.99 \times 0.2^2}{2} = 0.0998\ KN \times m$$

Subsequently, the required reaction force to compensate this momentum is calculated:

$$M = R \times a, \qquad R = \frac{M}{a} = \frac{0.065}{0.2} = 0.499\ N = 499\ kN$$

Then using a web calculator "Rough Calculation of Metric Bolt Size", the required cross-section of the bolt can be known. The result value is M6, which means the bolt should have a diameter of 6mm.

8.5.3. Water flow inside the soil

The selected soil substrate and the watering system should make sure that water will efficiently supply all the parts of the soil. Permeability helps the water flow through the soil but thanks to capillary forces it is prevented of going only downwards.

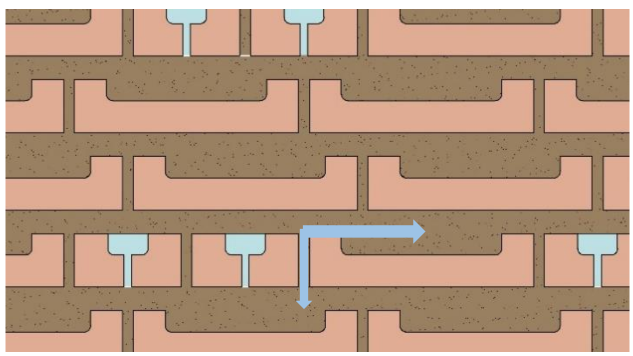


Figure 67: Water flow inside the soil of the wall (own work)

In order to prove this analytically, formulas regarding water flow in porous materials were researched. The most common equation, used to define water flow of a liquid through a porous material, is the Darcy's law. For Darcy's law it is assumed that the soil is fully saturated and that the flow inside the voids is laminar. For large soil pores and at high hydraulic gradient, flow may become turbulent. Then Darcy's law is invalid. Capillary forces are also not considered. In real life, the water flow may be driven as much by capillary forces as by the external hydrostatic head and capillary forces may often be dominant.

It is certainly true that construction materials are rarely saturated in use and that unsaturated flow is the main mode of mass transfer in building materials during construction and throughout their often long lifetimes. Even if materials or building elements are locally saturated from time to time, they are almost never saturated throughout and water migrates from the saturated regions to the unsaturated regions and ultimately back to the environment (Christopher Hall and William D. Hoff 2012).

Mathematical descriptions of liquid flow in porous media are based on Darcy's law. This states that the volumetric flow rate Q of liquid through a specimen of porous material is proportional to the length L of the specimen and to the cross-sectional area A (Christopher Hall and William D. Hoff 2012). Darcy's law is expressed simply as:

$Q = k \times A \times \frac{\Delta P}{L}$, m3/s (1)

Flow rate or Darcy's velocity: $u = \frac{Q}{A}$

(1) → $u = k \times \frac{\Delta P}{L}$, m/s

So far only flow in saturated porous media has been considered. However, as already mentioned, saturated flow is the exception rather than the rule in construction materials. The flow is described locally by the so-called extended Darcy equation where F is the capillary force and θ is the ratio of liquid volume to bulk volume. F is identified with the negative gradient of the capillarity potential Ψ, so that:

$$u = -K(u) \times \nabla\Psi$$

Combining this with the continuity equation leads to the fundamental equation of unsaturated flow, the Richards equation:

$\frac{\theta}{t} = \nabla k(\theta) \times \nabla\Psi$

Θ=Ψ and D=K, then:

$\frac{\theta}{t} = \nabla D \times \nabla\theta$

D is the capillary diffusivity. Most commonly the fluid is water and then D is called the hydraulic diffusivity (Christopher Hall and William D. Hoff 2012).

The formulation of the theory of unsaturated flow tends to neglect the gas-phase transport which accompanies that of the liquid phase. The theory as presented can be reconciled with a full two-phase theory in the limit that the gas-phase pressure is constant and equal to the external pressure. The assumptions have not been carefully investigated in relation to construction materials (Christopher Hall and William D. Hoff 2012).

The relationship between K(θ) and Ψ(θ) is defined:

$ux = -K(\theta)\frac{\Psi}{x}$

This defines horizontal flow of liquid through an unsaturated porous solid.

In fields such as hydrology, irrigation, the atmosphere, and waste management, the flow of water in partially saturated porous media is critical. It's also one of nature's most complicated flows. Richards' equation describes the flow of water in an unsaturated porous medium due to gravity and capillarity without taking into account the flow of the non-wetting process, which is normally air. (Farthing, M. W. and Ogden, F. L. 2017).

The numerical solution of the Richards equation remains computationally expensive and in certain circumstances, unreliable. There is yet to be defined a consistently robust and reliable solution approach that is applicable across the wide spectrum of soils, original, and boundary conditions encountered in practice (Farthing, M. W. and Ogden, F. L. 2017).

Due to the large mobility contrast between the water and gas phases, Richards' equation can be seen as a simplification of the conventional two-phase flow formulation for a gas and water phase in a porous medium, where the pressure gradient needed to drive flow of the gas phase is ignored. One of the most intriguing features of the Richards equation is that despite its ease of derivation, it is arguably one of the most difficult equations to reliably and accurately solve in all of hydro sciences (Farthing, M. W. and Ogden, F. L. 2017).

When accurate unsaturated flow simulation capability is needed, numerical solvers are required due to the lack of a general closed-form solution of the Richards equation. Because of the actual or perceived difficulties faced by the numeric methods, several estimated, analytical, or completely arbitrary methods have been developed over the years to simulate the flow of water through unsaturated soils (Farthing, M. W. and Ogden, F. L. 2017).

Consequently, a simple but still reliable way to validate that the system works and that water reaches the required distances, is with experimental experience.

9. Experiment

In order to test the effectiveness of the system, certain experiments were carried out. The main aspects to be tested are the water flow on the façade surface, the soil performance when assembling and in case of a rainfall and also the water flow inside the soil substrate.

9.1 Materials and tools

First of all, the required materials were gathered. In the basement of the faculty, there were a lot of unused soft mud molded bricks, left from previous experiments and available for anyone to use.

Figure 68: Existing bricks in the basement of the faculty (own work)

Apart from the bricks, drystack plastic strips and soil were needed for the experiment. A box full of drystack strips was provided at the office of building technology.

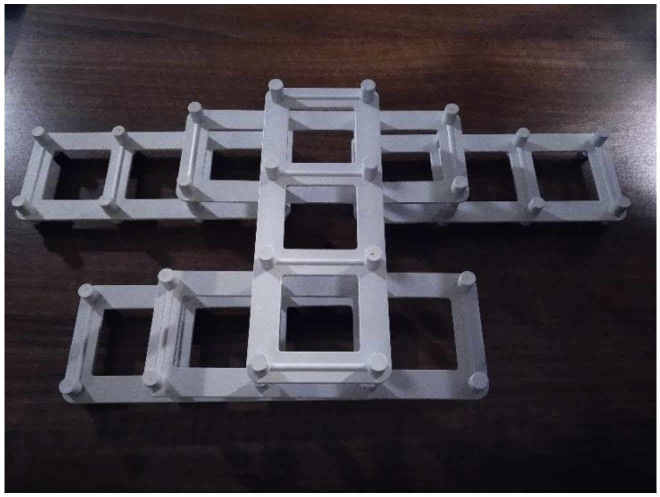


Figure 69: Drystack plastic strips (own work)

The two soils for the experiment, the TGS upper light substrate and the TGS lower light substrate, were brought by Erwin van Herwijnen at the faculty.

Figure 70: Soil bags (own work)

For the cutting process, one driller was used to make the holes on the bricks and one grinder to cut the notches.

Figure 71: Cutting tools, driller and grinder (own work)

9.2. Cutting

The first thing to do was to cut all the holes and the slits required. This took place outside the faculty and the cutting steps are shown on the diagram below. Luckily, the given bricks already had a frog, thus facilitating the procedure.

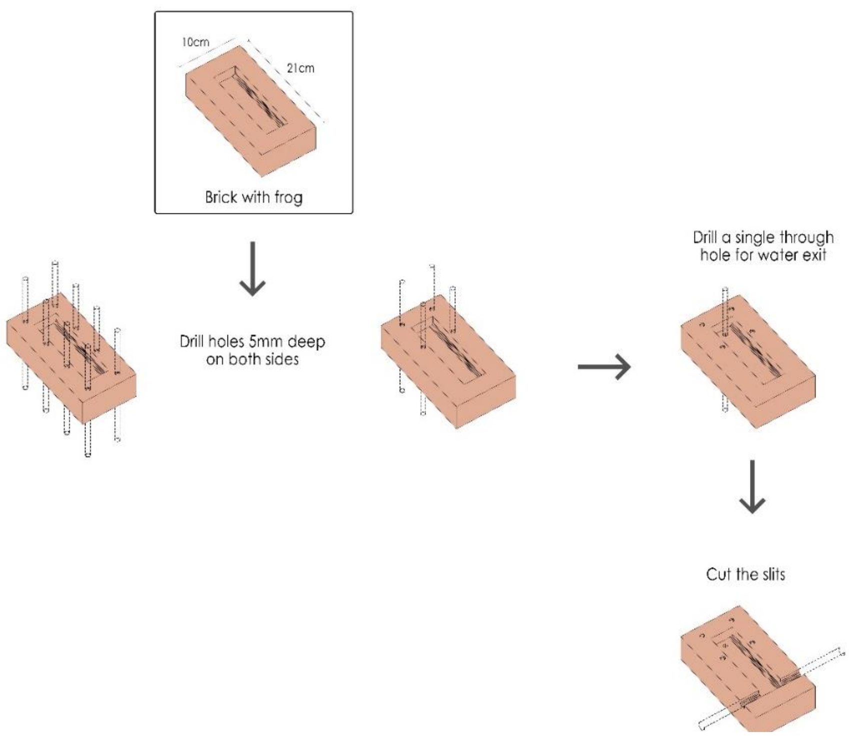


Figure 72: Brick cutting steps (own work)

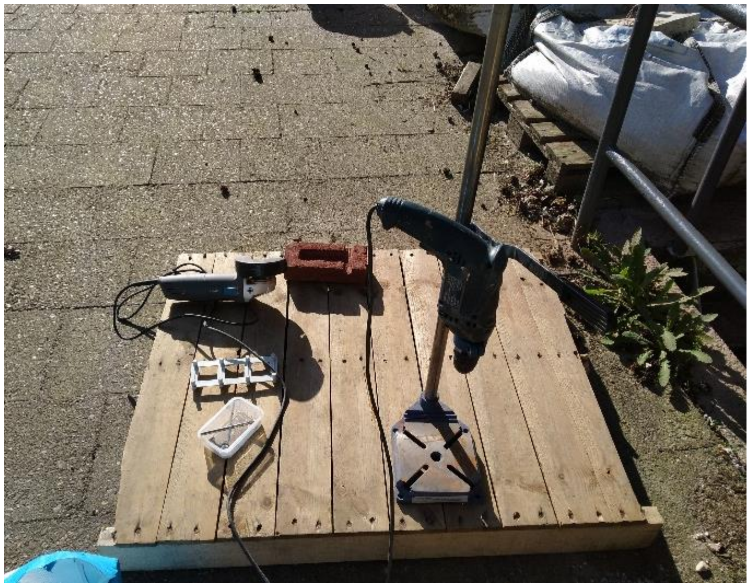


Figure 73: Working space (own work)

The 8 small holes were first drilled on 60 bricks and then half of the holes on another 14 bricks meant to be placed vertically.


Figure 74: Drilled bricks (own work)

After the drilling was completed, a draft assembling was done to make sure that it works fine.

Figure 75: Assembling test (own work)

Afterwards, notches had to be cut on those bricks aimed to be placed perpendicular to the wall. Along with the notches, a through hole was drilled on each of them.

Figure 76: Cutting notches (own work)

9.3. Water flow on the facade

Having all the components ready, the first experiment took place. This is related to the water flow from top to bottom starting from the orifice of the reservoir. A plastic box was used for the reservoir and different sizes of opening were tested to decide for the most suitable flow. The diameter sizes tested are 0.5 cm, 1 cm, 1.5 cm, 2 cm, 3 cm and 4 cm.

Figure 77: Water flow mock-up test (own work)

The outcome did not meet the expectations, while the water chose mainly its own way of escape and not the path indicated by the protruding bricks. The diameter of 0.5 cm results to a slow water flow and as the hole becomes bigger, the flow becomes impetuous. In order to control the water flow efficiently, the diameter of the opening should not be big, better not exceed the 1 cm.

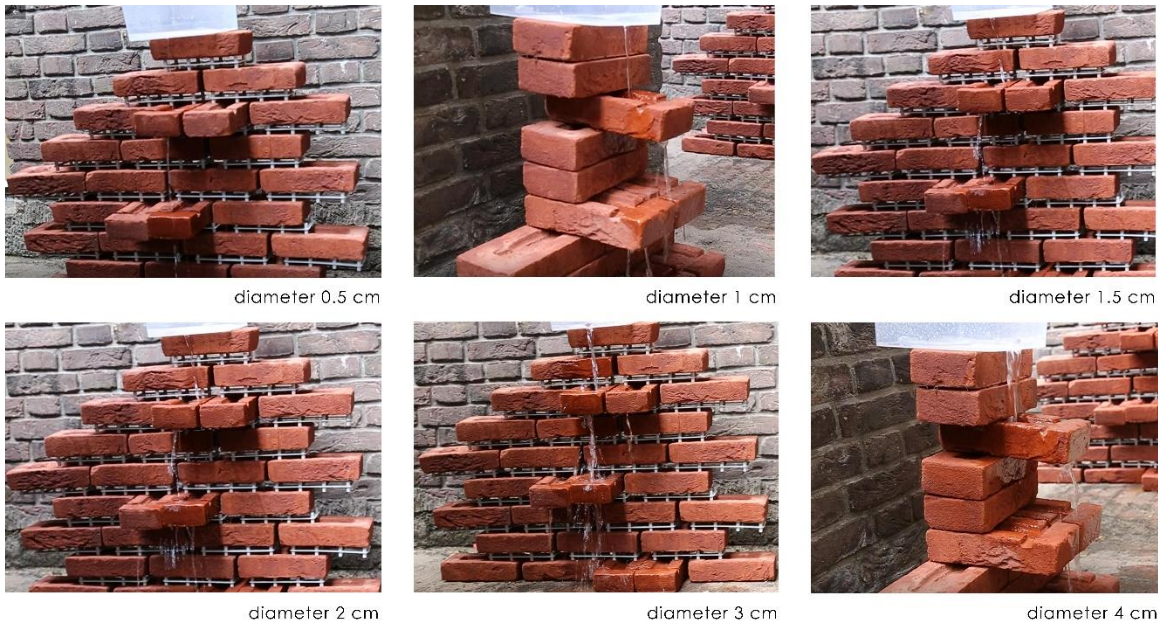


Figure 78: snapshots from the videos for the different orifice diameters (own work)

In the videos taken during the water pouring on the façade (figure 78), it is observed that the water flow is mainly guided by the surface friction of the brick and ends up falling outside the façade. One solution is cutting the notches more towards the middle of the frog and to overcome the surface friction, also chamfered sides of the brick may prove helpful. Additionally, water flow can be better controlled if there is a small tube attached to the hole of the reservoir.

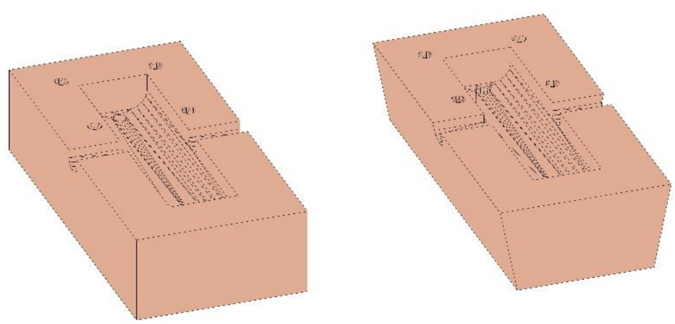


Figure 79: Notches cut to the middle, chamfered brick sides (own work)

Then, the experiment was repeated with a new water reservoir with an opening of 1cm diameter and a plastic tube attached to it (figure 80). The tube has a bit of conical cross-section and it was decided to attach it with both sides. Moreover, new bricks were cut with their notches at the middle of the frog.

Figure 80: Second water flow mock-up test (own

In the first attempt, the plastic tube is placed with its small cross-section attached to the plastic box and the larger side (1.5 cm) releasing the water towards the bricks. This is proven to increase the momentum of the water and although it flows from the notches, it goes farther than desired (figure 81 attempt a).

Then, the tube is placed upside down and the water flow is observed again. Now, water seems to be still affected by the frictions of the brick, maybe because the flow is smoother. However, considering that the notches are now in the middle, water is not exiting the façade but it keeps going downwards and will meet the next protruding brick below (figure 81 attempt b).

The last configuration tested consists of the same bricks but their sides are cut to become sloped. The water flow now is not guided by the brick surface and it follows mostly the desired path through the notches towards the next frog below (figure 81 attempt c).

Figure 81: Water flow- attempt a, attempt b, attempt c (own work)

Therefore, the last option works the best and thus the protruding bricks should be integrated accordingly.

9.4. Infiltration test of the soils

Together with the soil substrates, an infiltration testing apparatus was provided by Erwin van Herwijnen.

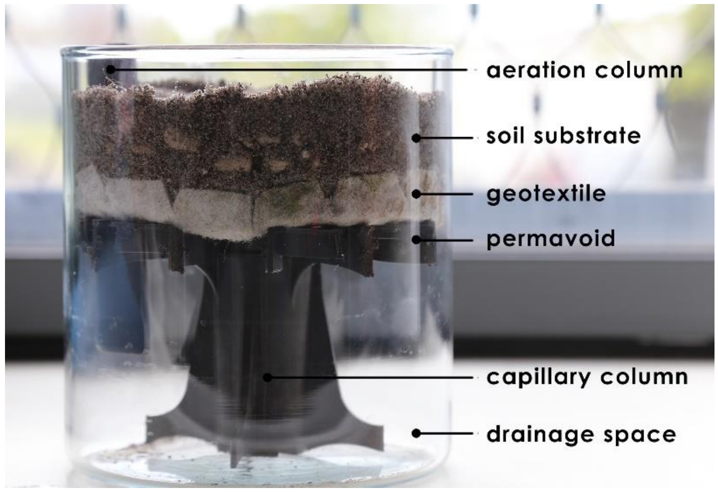


Figure 82: Infiltration test apparatus (own work)

This small apparatus consists of a glass bowl and a permavoid unit inside it. This unit is a plastic foundation replacement with a very high compressive strength, used to create functional drainage in the field of construction (Permavoid Head Office 2020). On top of it there is a geotextile, in order to spread the water effectively and let it drain evenly towards the bottom. Inside the permavoid there is a capillary fiber column with rockwool but its properties are not related to the project requirements.

The infiltration or percolation test is done to determine the water absorption rate of soil, related to the permeability of the soil substrate. Water is dropped on top, then flows vertically due to gravity and part of it is drained away.

$$infiltration\ rate = \frac{ammount\ of\ water\ (ml)}{time\ taken\ (\mathrm{min})} = x\ ml/min$$

The infiltration rate is the velocity or speed at which water enters into the soil. It is usually measured by the depth (in mm) of the water layer that can enter the soil in one hour. In dry soil, water infiltrates rapidly. This is called the initial infiltration rate. As more water replaces the air in the pores, the water from the soil surface infiltrates more slowly and eventually reaches a steady rate. This is called the basic infiltration rate (Coast Development Authority 2012).

Figure 83: TGS upper light substrate/ TGS lower light substrate (own work)

A small glass bowl was used to measure the soil mass. For both soils, the bowl was completely filled, in order to test the same volume (660 ml). Before conducting the experiment, the bowl was weighed with each of the soils and without. This measurement indicates that TGS lower light substrate is more lightweight than TGS upper light substrate with bulk density 670 kg/m^3 and 948 kg/m^3 respectively. It is important also to mention that both soil substrates were tested completely dry and were compacted when placed on the apparatus.

Table 11: Component used for the drainage test

Components used for the drainage test		
Component	**weight (g)**	**Volume (ml or cm^3)**
bowl	288	660
bowl + upper substrate	914	
bowl + lower substrate	730	
upper substrate	626	
lower substrate	442	
upper substrate g/cm^3	0.948	
upper substrate kg/m^3	948	
lower substrate g/cm^3	0.670	
lower substrate kg/m^3	670	
water addition	450	450

In advance of placing the soil on top of the rockwool, the apparatus was weighed and then weighed again after placing the soil. Afterwards, 450 mL of water was poured on top to observe the absorption of the soil. The same process is repeated for the other substrate, in order to understand the differences. The test was conducted five times and the results are indicated in table 12. For every test equal soil mass was weighed for each soil substrate.

Table 12: Drainage test results

				Drained water			Water holding capacity			
Drainage Test	**water addition (ml)**	**Upper substrate (g)**	**Lower substrate (g)**	**Upper substrate (ml)**	**Lower substrate (ml)**	**Difference %**	**Upper substrate (g)**	**Lower substrate (g)**	**Upper substrate (%)**	**Lower substrate (%)**
1*	450	626	442	214	336	-57.01	236	114	37.7	25.8
2	450	626	442	332	317	4.52	118	133	18.8	30.1
3	450	626	442	330	314	4.85	120	136	19.2	30.8
4	450	626	442	327	310	5.20	123	140	19.6	31.7
5	450	626	442	329	312	5.17	121	138	19.3	31.2
Average of Tests 2-5				329.5	313.3	4.9	120.5	136.8	19.2	30.9

* Test 1 is false and excluded from the average

The first test was probably false since the results were significantly different than those of the consequent four tests with very similar results. This outlier has to do possibly with the procedure steps. When the test was first conducted, the apparatus was used twice, first to test the TGS upper light and secondly to test the TGS lower light. However, the water amount gathered inside the capillary tube from the first attempt was not considered. Thus, during the first soil test the tube was dry, whereas during the second soil test, it was wet and affected the results by increasing the water portion gathered at the bottom. In order to avoid such inaccuracies it was then decided to always fill the capillary column with water for each consequent experimental test.

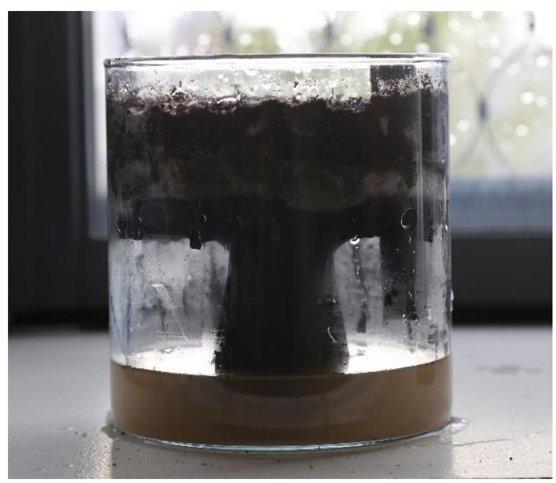


Figure 84: First test attempt results: TGS upper light substrate, TGS lower light substrate (own work)

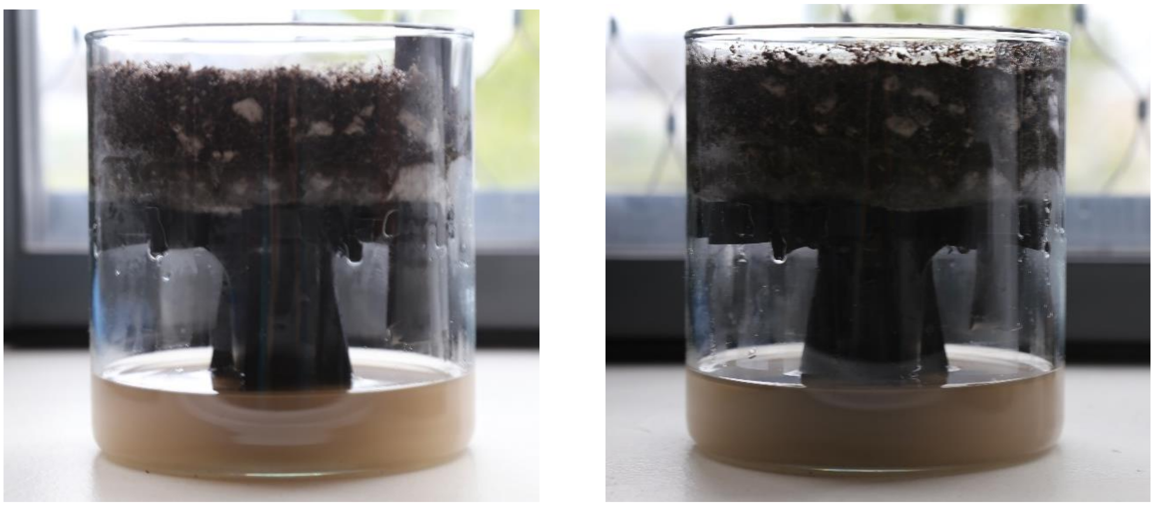


Figure 85: Second test attempt results: TGS upper light substrate, TGS lower light substrate (own work)

From this experiment it is concluded that the hypothesis of TGS lower light having a better drainage, is false. In fact, the TGS lower light substrate has lower drainage capacity but higher water retention, highly depending on the pore size and pore connectivity. The reason lies possibly in the presence of pumice and TGS lower light substrate has high volumetric content 39% of pumice comparatively to the 25% of upper substrate. It is well known that pumice is highly porous, with a porosity range of 64-85 %. It has roughly the consistency of a mixture of gravel and sand with light porous individual granules. Pumice particles have up to 65 mm diameter, including powder (0-2mm), sand (2-8mm) and gravel (8-65mm). (Caiza, M. et al. 2018)

To conclude, opting for the maximum drainage suggests that the upper light substrate is the best choice. The disadvantage though is that the water holding capacity is low, 19% in the tests. This particularly means the soil substrate dries faster and as a result irrigation requirement is higher.

9.5. Wall assembling

Subsequently, a further comparison of the soils is carried out and it is achieved by assembling a wall part and observing their performance.

The first soil used is the TGS upper substrate light. The soil was a bit compacted before placing it and then it was carefully positioned on each layer between the bricks. It got a bit wet when assembled, by spraying water on it and thus compacting it more easily.

Figure 86: Assembling process of the wall with the TGS upper light substrate (own work)

Figure 87: Assembled wall (own work)

After assembling the wall, water was poured on the frogs of the protruding bricks to check the stability of the soil consistency. Where the water was inserted, there was a big soil erosion. This may be happening due to the high percentage of sand particles in the soil but the conditions of the experiments should be also taken into account. No equipment was used and the consistency of the soil before placing was not very well compacted and wet.

Figure 88: Erosion of the soil substrate after water pouring

One day later, the wall was demounted and reassembled using the TGS lower substrate light. Considering the steps and the results of the previous assembling, the procedure was a bit altered in order to make the soil more compact. Thus, before placing the soil, first it was very well wet and compacted to create a solid mass, resembling the mortar consistency. Then all the layers were carefully placed and pressed to cover all the gaps. The assembling process became easier and the soil mass better to handle.

Figure 89: TGS lower light substrate wet and compacted before assembling (own work)

Figure 90: Assembling process (own work)

Figure 91: Assembled wall (own work)

After assembling, the substrate already seemed more stable and compact. Water was poured inside the water frogs and there was no soil washed out. However, this should be tested again when the soil will be totally dry because that is when the wash-out risk becomes higher.

Taking into account, the altered procedure for the second soil substrate, they should be both compared under the same conditions. Thus, it was decided to repeat the process with a small wall part assembling. Both soil substrates were wet and compacted with the same way and then assembled accordingly. They are left to dry and then water is going to be poured inside the frogs to examine their stability and the erosion risk.

Figure 92: Wall part on the left composed with TGS lower light substrate and wall part on the right with TGS upper light substrate (own work)

9.6. Water flow inside the soil

In order to test the water flow inside the soil, two experiments took place. The first is related to the moisture levels of the assembled wall and the second deals with capillary rise inside the soil.

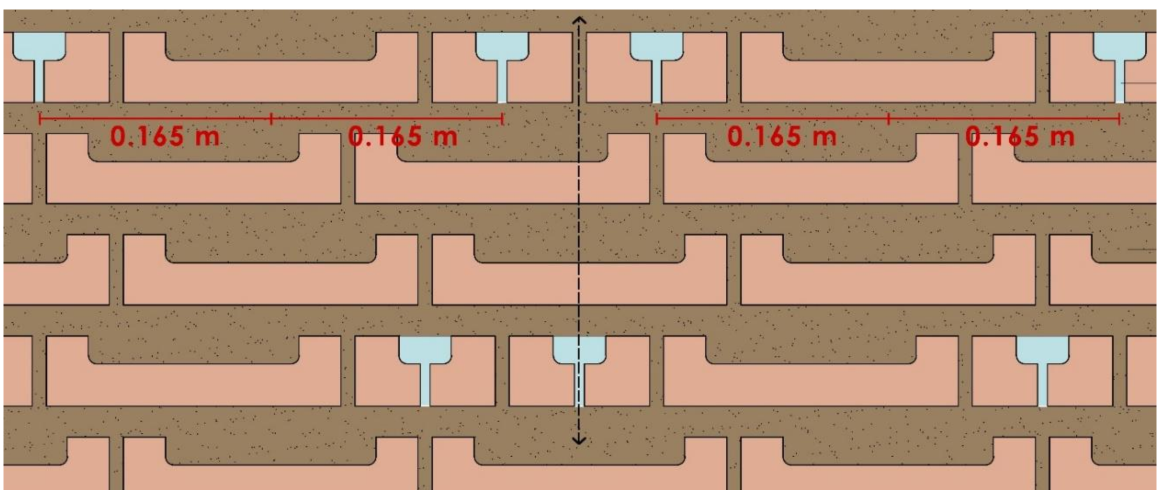


Figure 93: Farther distance that water has to reach (own work)

For measuring the moisture, one should consider the maximum horizontal distance that water needs to reach when penetrating inside the soil. This is 0.165 m as indicated in figure 93. It is the half distance between the through holes of two linear protruding bricks. Water exits from these holes and spreads towards all directions. However, mostly led by gravity, horizontal flow is not dominant and it needs to be secured that the maximum horizontal distance is reached.

9.6.1. Moisture test on the assembled wall

In order to measure the moisture content (MC) of the substrate before and after irrigation two samples are taken. One soil sample is taken from the wall at the 0.165m distance in order to measure its initial MC. A second sample is taken after pouring 60 ml of water inside the frog of the brick. The amount dropped is defined by the volume of the frogs, whose sum gives the total amount exiting the water reservoir. The volume of one brick frog is 5.6e-5 m3 (56 ml). The second sample is taken from the mirror distance defined by the center axis of the two protruding bricks, thus at an identical to the first sample wall position.

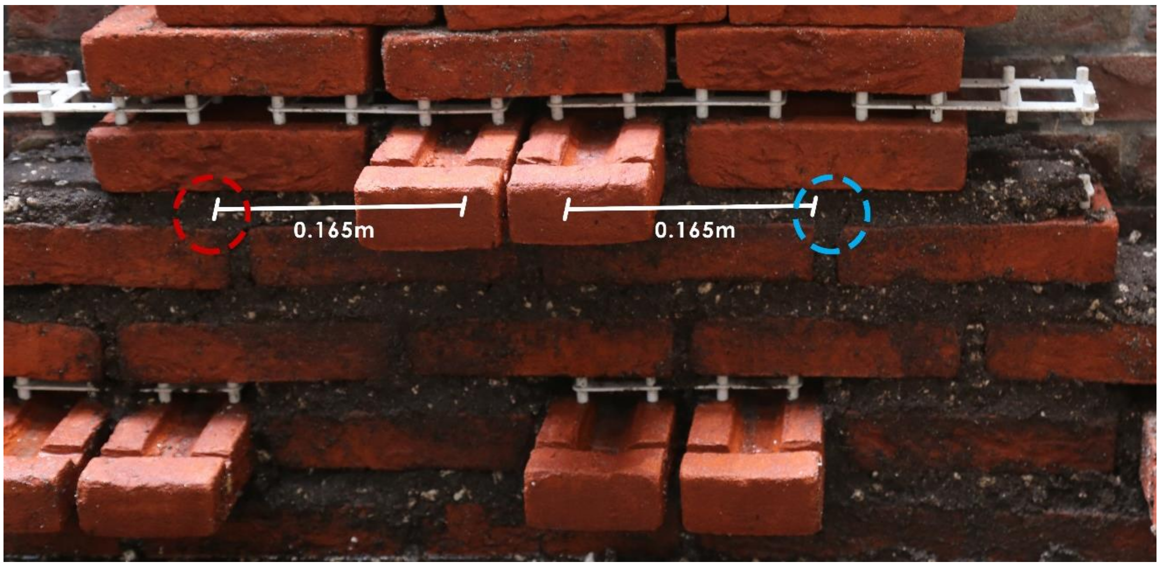


Figure 94: First soil sample indicated by red circle and second sample indicated by blue circle (own work)

Figure 95: Picture taken after removing the samples (own work)

Initial weighing of the two samples gives the wet weight. Then, they are dried at 100 °C in the oven for two hours and then weighed again to get the dry weight. The first sample gives the weight of the semi-saturated soil, which keeps water while assembling. The second sample indicates the weight of the soil when water is inserted by the frog. The table 13 shows the initial wet weight, the dry weight and by calculation the percentage of water content. The water content increase after irrigation is 3.3%.

Table 13: Weight measurement

Sample	Wet weight (g)	Dry weight (g)	Water (g)	Water (%)
1	99	65	34	34.3
2	109	68	41	37.6
Water Increase after irrigation (%)				3.3

Table 14: Soil Water absorption

Water Increase after irrigation (g or ml)	3.6
Irrigation dose (ml)	60
Soil water absorption (%)	5.9

Figure 96: weight of 1st soil sample and 2nd soil sample (own work)

With water content increase 3.3% after irrigation with 60 ml, the water absorbed by the soil at the certain position is 5.45% and 6 for sample 1 and 2 respectively, or 5.72% in average.

For testing the moisture content through time, it was then decided to repeat this experiment with certain alterations. Water is poured in the two frogs of the protruding bricks, which determine the central axis. After 15 minutes two samples are removed from one side defined by the central axis and their weight is measured. Then after 30 minutes, two identical samples are removed from the mirror side of the axis and their weight is measured as well (figure 97). Then they are oven dried at 100 °C, in order to measure their dry weight.

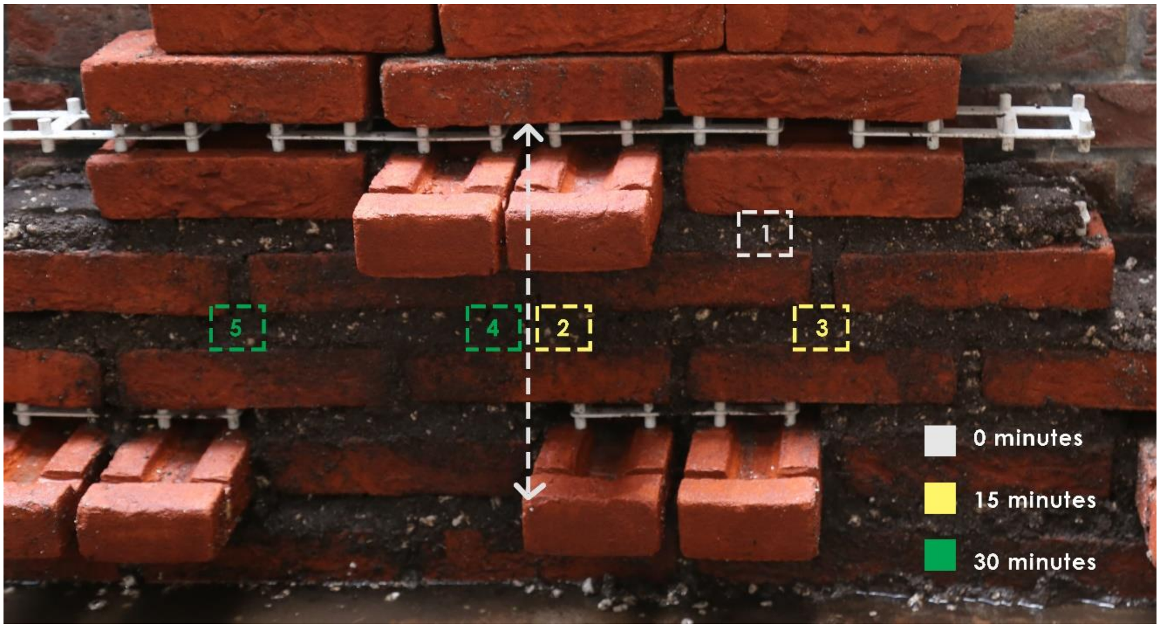


Figure 97: Samples taken in different times

Table 15: Moisture content of different samples in different times

time (min)	Sample	Wet weight (g)	Dry weight (g)	Water (g)	Water (%)	Water Increase after irrigation (%)	Water Increase after irrigation (g or ml)	Irrigation dose (ml)	Soil Water absorption (%)
0	1	35	28	7	20				
15	2	29	22	7	24.14	4.14	1.2	60	2
17	3	32	24	8	25	5	1.6	60	2.7
30	4	44	33	11	25	5	2.2	60	3.7
32	5	48	35	13	27.08	7.08	3.4	60	5.7

From table 15 it can be understood that soil water absorption increases with time, meaning that a certain duration is required for water to spread to all of the soil mass.

9.6.2. Capillary tube test

The next experiment, conducted to understand the water flow inside the soil substrates, is a capillarity test. The height that water can reach due to capillarity is analogous to the horizontal length it can reach in the façade system. The experiment should consider two extreme situations. The one extreme situation considers continuous contact of free water with the soil. This may happen when there is continuous refill of the protruding bricks by heavy rainfalls. The other extreme situation considers a short time contact. The time is calculated according to how long the water stays inside the frog, which is measured 35 seconds after pouring 60 ml. This can happen during dry periods that the façade receives only the required amount of water from the reservoir on top. Then, a third situation was considered regarding the second extreme but instead of timing the contact with water, the portion of water was only measured to be 60 ml.

An acrylic transparent tube is used and cut in two parts in order to be filled with the two substrates in question. The chosen diameter of the tube is 6cm and subtracting the thickness of 2mm, it is 5.6cm. The cross-section is then 24.6 cm^2 which is similar to the actual cross-section of the soil substrate in the façade system (24 cm^2).

The test is conducted three times considering the different situations mentioned. First time, the two tubes remain inside water and the capillary rise is recorded to check the time that water reaches a certain height. Then, the process is repeated but the tubes are left inside water only for 35 seconds. Then they are removed and it is observed how water continues rising due to capillary forces and what is the maximum height that it reaches. Finally, the process is repeated with the tubes left inside 60 ml of water each and the capillary rise is again observed.

Figure 98: Capillarity experiment/ lower light substrate on the left and upper light on the right (own work)

Starting with the extreme situation that considers continuous contact with the water, the results indicate that water will reach and even exceed the maximum distance of 16cm, with a duration of around 5 hours (300 minutes).

Table 16: First situation, capillary rise of the two substrates

	capillary rise (cm)	
time (min)	TGS upper light	TGS lower light
1	4	2.5
2	6	4
10	8	6
30	10	8
60	11.5	10.5
120	16	16
300	22	22
max	22	22

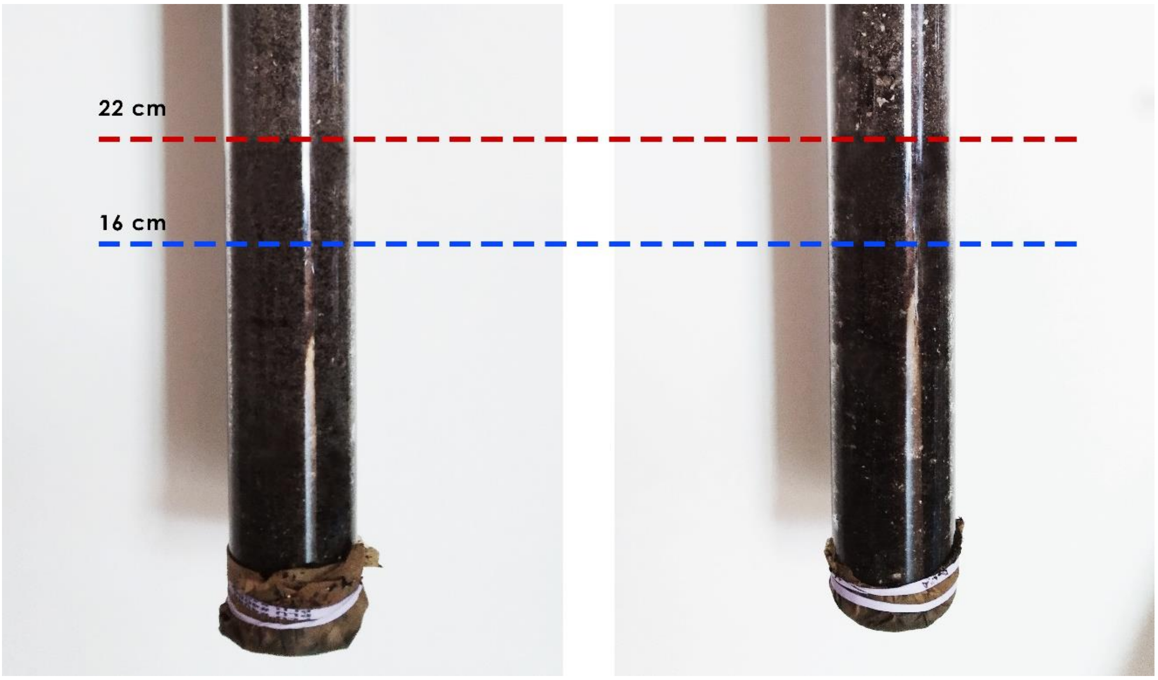


Figure 99: Capillary rise after continuous contact with water, upper light substrate on the left and lower light substrate on the right (own work)

Then the process is repeated considering the opposite extreme situation, for which the contact between water and soil lasts only 35 seconds. The two tubes were placed inside water for 35 seconds (0.58 minutes) and then they were removed to record the capillary rise. The maximum height is reached in 30 minutes and it is 4cm. The short time of contact between water and soil, does not allow water to reach the required distance and above 4cm the soil mass remains dry.

Table17: Second situation, time and heights reached due to capillarity

	capillary rise (cm)	
time (min)	TGS upper light	TGS lower light
0.58	2	1
1	3	2.5
10	4	3.5
30	4	4
max	4	4

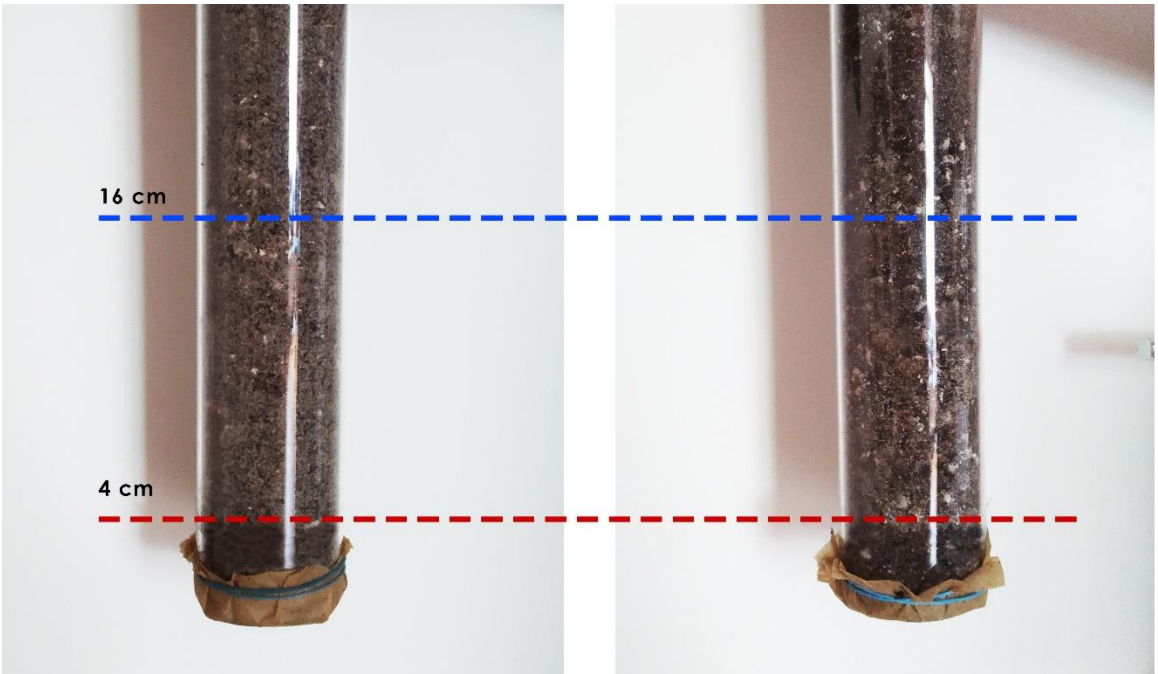
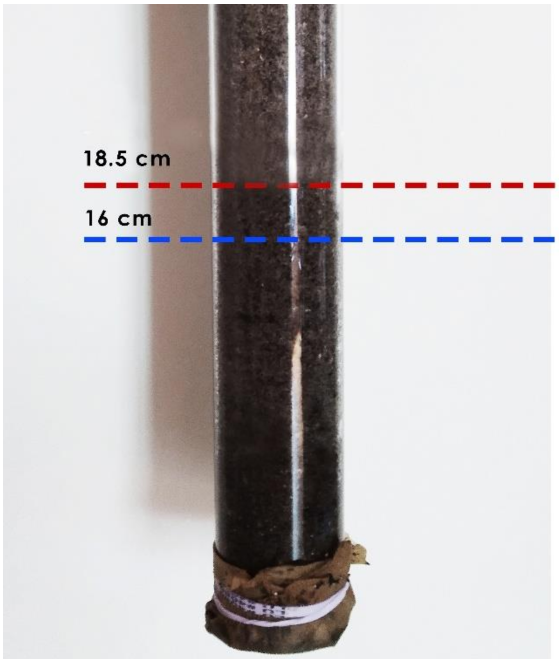


Figure 100: Capillary rise after short contact with water, upper light substrate on the left and lower light substrate on the right

The last experiment regarding capillarity is then conducted. The tubes filled with the two soil substrates are placed each inside a bowl with 60 ml of water. As it is indicated in table 18, the maximum required height is reached after a certain duration and it is again exceeded but with a lower maximum than the first situation. The 60 ml of the bowl are completely absorbed by the soil substrate and the bowls are found empty when the maximum capillary rise is reached.

Table18: Third situation, time and capillary heights

	capillary rise (cm)	
time (min)	TGS upper light	TGS lower light
1	4	3
2	6.5	4.5
10	8	6.5
30	11	9
60	12	11
120	15	14
300	18.5	18.5
max	18.5	18.5



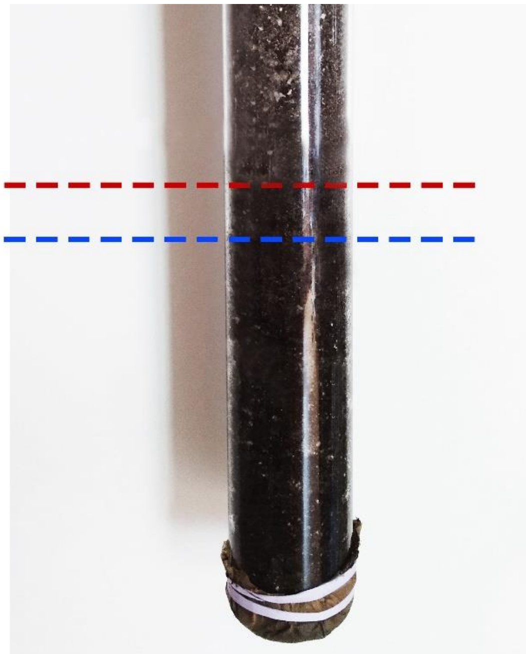


Figure 101: Capillary rise considering 60 ml of water, upper light substrate on the left and lower light substrate on the right

However, it is important to measure the exact moisture content through the soil substrates at various heights. It is possible that water rises higher than what is visible. This is achieved by dividing the tube into 5 equal layers of 10 cm and then the water content is measured by weighing each soil layer once right after removing it from the tube and again after oven drying for 2 hours at100 °C. Each portion was removed with a long spoon while holding the tube horizontally.

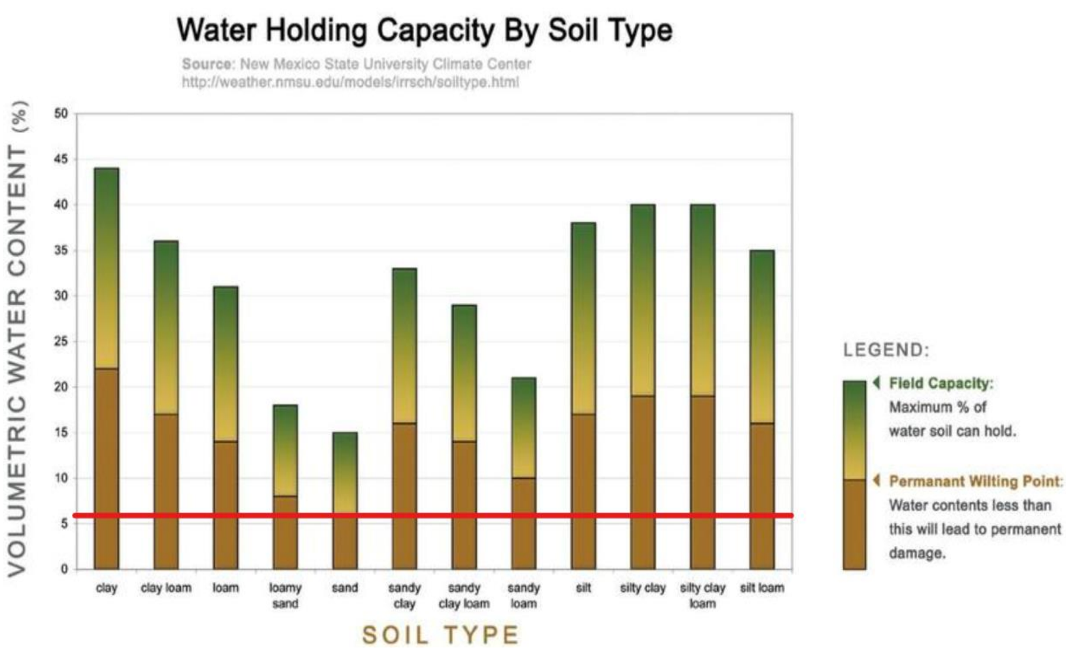


Figure 102: Water holding capacity by soil type (Research gate < https://www.researchgate.net/figure/Figure-K-Water-holding-capacity-VWC-for-different-soil-types-NMSU-Climate-center_fig12_319929493>)

Both TGS substrates consist mostly of sand and they are defined as sandy soils (figure 63). As shown in the diagram of figure102, sandy soils have low Field Capacity and Available water content. However, they also have low wilting point, around 6% volumetric soil water content % (red line). This is the minimum for any plants to grow properly and receive sufficient amount of water.

The amount of water or moisture in soil can be measured as either gravimetric soil water content (GWC) or volumetric soil water content (VWC). GWC is the mass of water per mass of dry soil in a given sample. VWC is the volume of water per volume of soil (Edaphic scientist). To derive VWC, a sample should be measured wet and dry and the bulk density (BD) should be known. The equation for VWC is given:

$$VWC = GWC \times BD$$

Table19: Moisture content in the different parts of TGS upper light substrate

		TGS upper light					
parts	length (cm)	saturated weight (g)	dry weight (g)	difference	GWC %	BD g/cm^3	VWC %
1	0 to 10	374	290	84	22.5	0.948	21.3
2	10 to 20	345	286	59	17.1	0.948	16.2
3	20 to 30	296	266	30	10.1	0.948	9.6
4	30 to 40	248	245	3	1.2	0.948	1.1
5	40 to 50	254	251	3	1.2	0.948	1.1

Table20: Moisture content in the different parts of TGS lower light substrate

		TGS lower light					
parts	length (cm)	saturated weight (g)	dry weight (g)	difference	GWC %	BD g/cm^3	VWC %
1	0 to 10	339	240	99	29.2	0.67	19.6
2	10 to 20	303	237	66	21.8	0.67	14.6
3	20 to 30	280	226	54	19.3	0.67	12.9
4	30 to 40	231	227	4	1.7	0.67	1.2
5	40 to 50	229	225	4	1.7	0.67	1.2

The results shown in tables 19 and 20 prove that water actually rises higher but the moisture content percentage reduces gradually. Red indicates that the percentage is below the permanent wilting point (6%) and it is not considered adequate for the plants.

This process is repeated for the second extreme situation, which had the lowest capillary rise. The tubes are filled again with the two soil substrates completely dry. Then after placing them in water for 35 seconds, they are left for a while to reach their maximum capillary rise. The tubes are then divided into 10 equal layers of 5 cm. Each layer is removed to measure its saturated weight and also its dry weight after 2 hours in the oven. The process ends when the moisture content is found stable and close to 0%. Dry weight and oven dry weight may differ slightly to a very sandy soil substrate, which was provided dry (air dried) with very low moisture content. Nevertheless, it still has some water very strongly held by adhesive forces or trapped into isolated micro pores, which may be removed only if it is oven dried at 100 – 105 °C). As can be seen in tables 21 and 22, capillary rise is higher than observed with naked eye (4 cm) but only a very small moisture percentage reaches until 15 cm height.

Table21: Moisture content in the different parts of TGS upper light substrate

		TGS upper light					
parts	length (cm)	saturated weight (g)	dry weight (g)	difference	GWC %	BD g/cm^3	VWC %
1	0 to 5	175	142	33	18.9	0.948	17.9
2	5 to 10	148	140	8	5.4	0.948	5.1
3	10 to 15	143	137	6	4.2	0.948	4.0
4	15 to 20	139	138	1	0.7	0.948	0.7
5	20 to 25	141	140	1	0.7	0.948	0.7

Table22: Moisture content in the different parts of TGS lower light substrate

		TGS lower light					
parts	length (cm)	saturated weight (g)	dry weight (g)	difference	GWC %	BD g/cm^3	VWC %
1	0 to 5	169	131	38	22.5	0.67	15.1
2	5 to 10	145	127	18	12.4	0.67	8.3
3	10 to 15	134	126	8	6.0	0.67	4.0
4	15 to 20	128	127	1	0.8	0.67	0.5
5	20 to 25	126	125	1	0.8	0.67	0.5

However, considering that capillary rise reaches 15cm (almost 16cm, maximum required distance), the contact time with water could be slightly increased, in order to increase also the moisture content.

9.7. Results

Firstly, it is worth mentioning the limitations affecting the experimental work. The lack of equipment may have caused certain inaccuracies in the way the experiments were conducted. Additionally, the working surface, where the wall was assembled, is not flat and straight, thus influencing the alignment of the system elements. Concerning the infiltration test, the apparatus used is quite small and maybe it is not revealing the real differences of the soils' drainage. Last but not least, the compaction of the soil substrates inside the acrylic tube for the capillary tube test was not done with the proper equipment or machines and may have affected the outcome.

Considering the optimal selection of soil substrate, they have both performed very similarly and it is difficult to define which one is better. There are only slight differences detected which could lead to a final selection. In the assembling experiment, the lower light substrate was easier to get compacted and its consistency seems a bit more bonded. In the infiltration experiment, the lower light substrate was proven more lightweight than upper light substrate with bulk weight 670 kg/m^3 and 948 kg/m^3 respectively. The lower substrate had significantly lower drainage capacity and consequently higher water holding capacity. Lower light substrate retains 31% of the water poured, while upper light substrate retains only 19%. As far as the wash-out risk is concerned, both substrates perform well and they seem to resist erosion effectively. However, if wash-out happens in future monitoring or in case of extreme rainfall, improving the consistency of the substrate may be the solution. The soil substrate could be further mixed with some kind of binder material. Further optimization could be achieved by adding a biological glue in order to reduce weathering. Otherwise, there could be a perforated membrane added on the outer surface of the wall to control the erosion.

Figure 103: no wash-out after pouring water inside the frogs (own work)

Finally, in the capillarity experiment, both soil substrates had the same capillary rise, but they differ in the duration of reaching certain heights. It was noticed that water took more time to rise to a certain height inside the lower light substrate but after a while they kept going parallel. One other remark is that the water inside the lower light substrate seems more homogeneously spread (figure 104), while water inside the upper light substrate seems highly retained at the bottom and less as it goes up. Considering the moisture content measured for the different soil parts, the volumetric soil water content (VWC) is similar throughout the soil mass for both substrates. The only difference is that the TGS upper light substrate has a lower than 6% VWC already at part 2 (5-10cm), while the VWC of TGS lower light is 8.3% at part 2 and become less than 6% after the 10cm (tables 21,22). This means that it can provide capillary water to the plants at higher distance. From these remarks, it can be concluded that TGS lower light substrate is more suitable for the current project.

Figure 104: capillary rise, lower light substrate on the left and upper light substrate on the right

From the capillarity experiment it is also concluded that in case of one watering, water may not reach the maximum distance required. Nevertheless, the experiment conditions are not totally realistic, while the required distance is actually horizontal and not vertical. The soil mass placed inside the tubes was completely dry, which is hardly ever the real condition of the soil substrate on the wall, where it retains moisture for long. Capillary rise will be higher in a moist soil with one watering, because its pores already contain some water. Moreover, another aspect which should be considered is that plant roots will grow towards higher soil moisture (figure 105). Nonetheless, when plants are planted, their roots initially very short, are unable to exploit large soil volume and remote moisture. Thus, irrigation should be more frequent with low doses, or using sometimes higher irrigation doses in order to moisten larger soil mass and secure that plants meet their water needs.

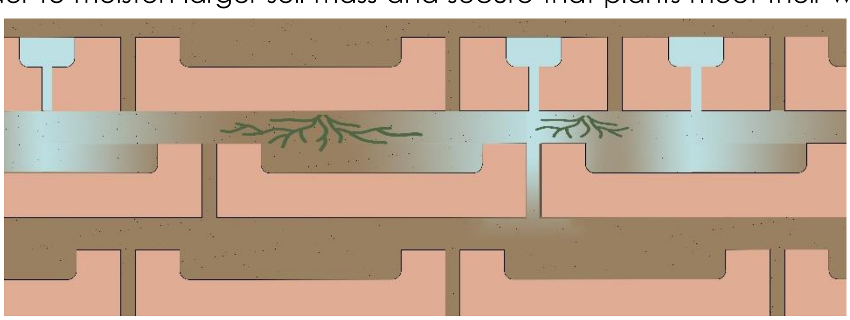


Figure 105: Roots growing inside the soil substrate and towards water

Attention should be given to the fact that very young plants are vulnerable to rot roots if soil moisture is very high.

9.8 Improvement of design system and components

The experience gained from the experimental work has also an impact on the system design. First of all, certain alterations could be proposed for the drystack elements. Considering the already existing components, a new one could be a stopper on the sides of the façade, which could keep the soil substrate more stable. Additionally, the DS layer could become more flexible by creating variations, in terms of the distances between the plastic studs. This can possibly allow the growth of bigger plants and may also offer an interesting pattern to the façade.

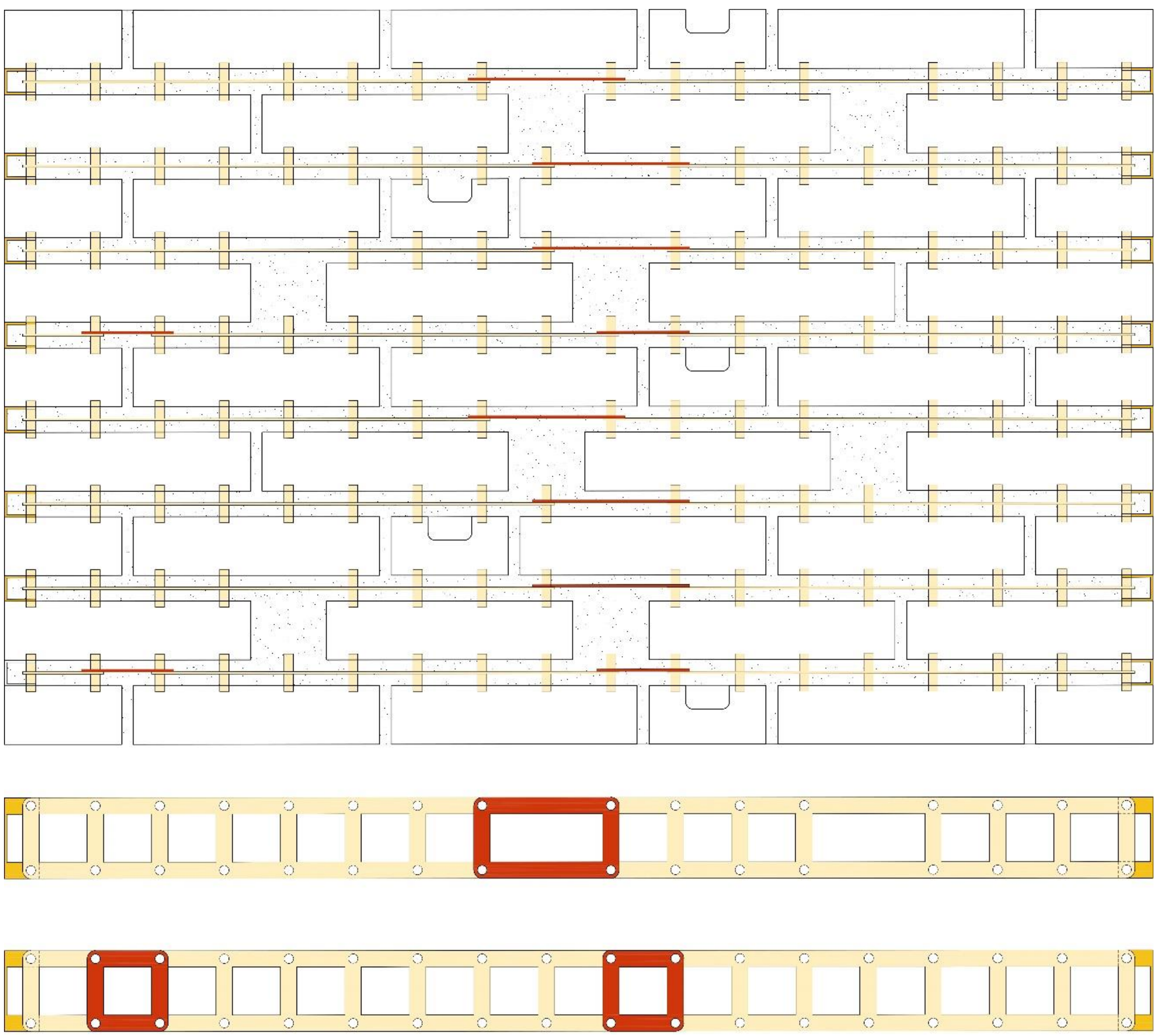


Figure 106: Drystack alterations: yellow → DS side Stopper, red → DS Bridge, (own work)

Furthermore, an optimization of the protruding bricks is required in order to control the water flow better. Cutting the notches towards the middle of the frog prevents the water of splashing out and keeps it mostly aligned with the surface. For further integration, the bricks with sloped sides were proven more suitable because water follows its path through the notches and it is not so much affected by the frictions of the brick surface (figure 79). However, this also affects the manufacturing, by increasing complexity. There is no existing mold at this shape, meaning that a new mold has to be created for this project. Moreover, considering the goal for a sustainable product, bricks with this shape are more difficult to be reused for other purposes. Therefore, taking into account also these disadvantages, the brick with only cutting notches to the middle could also meet the requirements, even if water flow is not optimal as it is for the brick with chamfered sides.

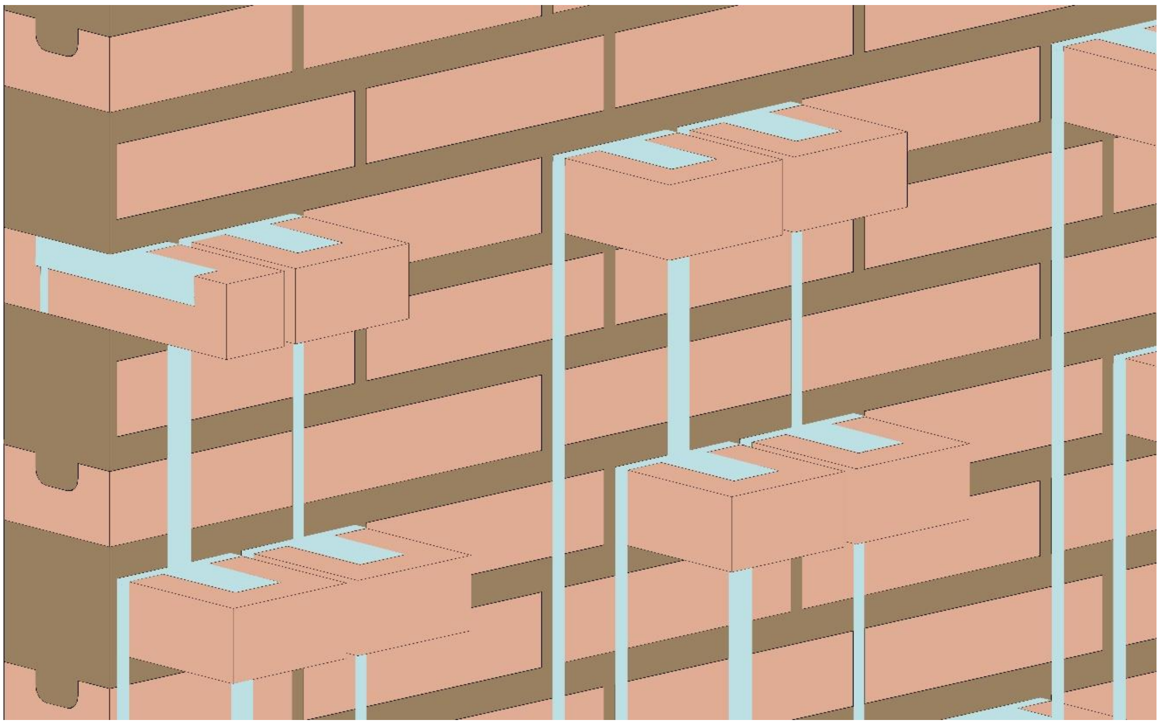


Figure 107: Water flow with the new protruding bricks (own work)

Additionally, during the experiment it was noticed that there is a risk of dust or any external substance to gather inside the through holes at the bottom of the protruding bricks. One solution could be to fill them with the soil substrate. This may also slow down the water absorption and increase the time of water contact, which then increases the capillary rise. Moreover, a conical cross-section may facilitate soil filling, as well as the transportation of water inside the soil substrate.

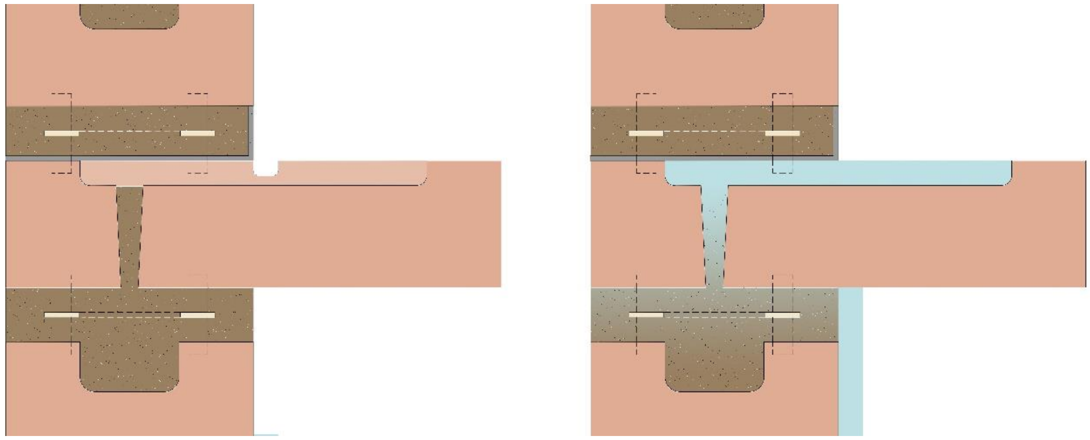


Figure 108: Conical through hole filled with soil (own work)

Furthermore, the experiments helped in understanding the assembling process and difficulties. These can define certain requirements regarding the optimal selection of buildings for the most efficient application of this façade system. Apart from belonging to the low-cost social houses of 1970, they should share certain characteristics:

- Long and straight façade surfaces
- Simple building shape
- Lack of insulation

Figure 109: Suitable buildings for renovation, located in Delft

The buildings shown in figure 108 are edifices, located in Delft, that meet these requirements and could become candidate products for renovating their façade.

The assembling steps should be also pointed out, indicating the application's feasibility and simplicity. These are better explained with figure 110. At this point, it is also important to mention that plants are going to grow with the help of seeds incorporated inside the soil substrate. Planting the plants in a later stage would be rather difficult and time consuming.

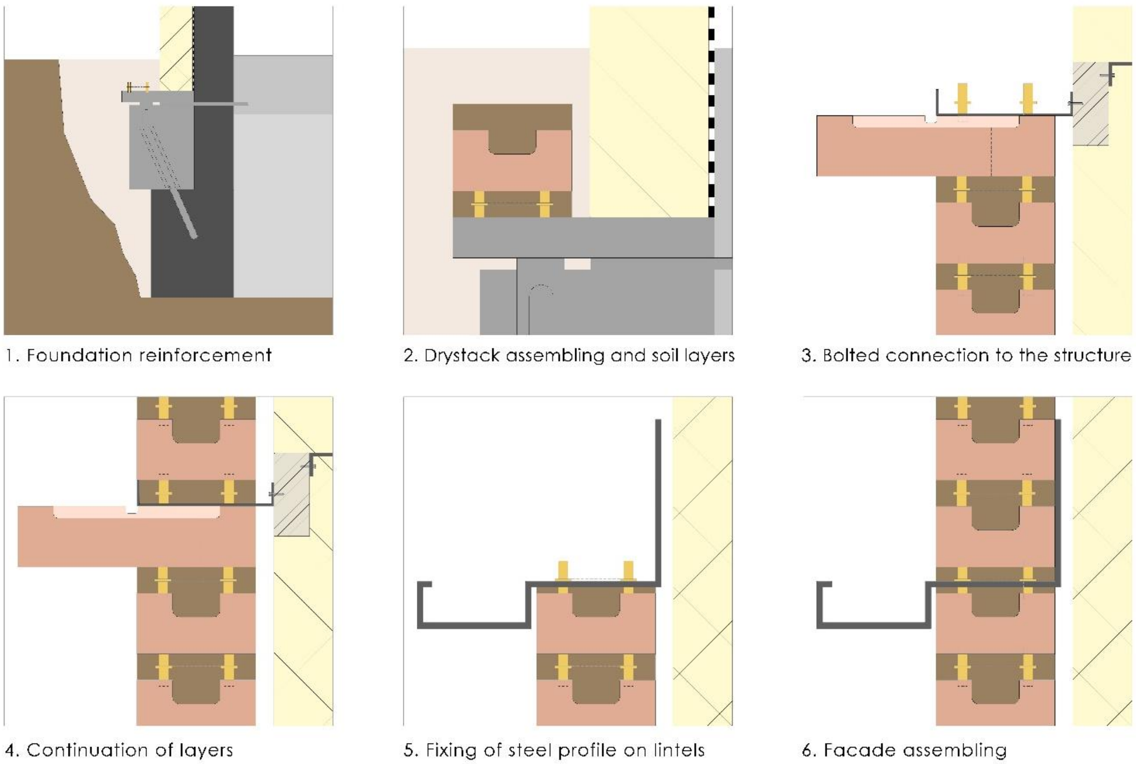


Figure 110: Assembling steps for renovating old facades (own work)

10. Conclusion

The aim of this thesis was to give an answer to the main research question: How can a brick façade system be composed in order to allow plants and building materials coexist efficiently on wall surfaces?

The research question was followed by certain sub-questions defining the main aspects that need to be researched and solved in order to make this project succeed. These are the structural stability, the plants, the substrate that secures their growth and an efficient watering system.

The literature study firstly provided this research with useful knowledge to understand those aspects and their challenges. Design innovations are also explored to define existing products with similar expectations and provide the current project with relevant experience.

When analyzing the design proposal and the steps leading to the final solution, it can be understood that the façade designing is strongly dependent on the watering system. The protruding bricks and the created pattern principally serve the purpose of watering functionality and secondarily also an aesthetic purpose. Simplicity determines the design steps, seeking for a clear solution, easy to be assembled, demountable and sustainable.

The building case study provides this thesis with the actual challenge of solving this new system on a real field. Renovation of this old building required addition of insulation and certain reinforcement of the foundation in order to support the renovated façade. Trying to adjust the system in the given surface areas including also windows and openings, was quite challenging but facing these problems is proven very useful. For water avoiding the openings when flowing on the façade, the design had to be further improved and offer a satisfying solution. Renovation of buildings, similar to the case study, can improve their performance and also the quality of the city.

After finalizing the design proposal, the components of the system are discussed and selected according to the project requirements. The type of brick was easily decided thanks to relevant research and the drystack elements are already defined by the drystack company. However, certain alterations and new ideas are proposed for the drystack elements to achieve further design flexibility.

The plant species selection demanded deeper research and the help of experts to find suitable plants that can survive and coexist under the given conditions. The ones selected seem to make a feasible choice because of their characteristics but they should be further tested in the future and see their real growth behavior. They are, however, totally dependent on the substrate choice. This was even more researched in order to understand the main factors related to water flow inside the soil and to those defining at the same time a compact and lightweight soil structure that can efficiently perform on vertical surfaces. The soil substrate selection was further corroborated by experimental experience thanks to the two soil substrates provided by the TGS Company.

The last component of the system is irrigation, achieved with the water reservoir and the protruding bricks. This part is accompanied with calculations determining the required water volume and the duration that watering takes place. In order to keep the duration fixed for all the different wall surfaces of a building, the orifice of the reservoir changes accordingly, considering that water flow and velocity are proportionally related to the cross-section of the opening from which water exits. One very important advantage of the reservoir is its water capacity that ensures a maximum of 8 times of watering during dry periods. However, for other countries with drier climate, this capacity may not be enough and further integration would be required to provide the system with more water when it is needed. The challenge would be to solve this by maintaining the system natural and not by using mechanical pumping systems. This remains to be solved for further use of this system worldwide. The water reservoir is also solved structurally to make sure that the façade system can receive its load and that the momentum of the protruding part is compensated by the structure.

Water flow in soil was also researched to be solved analytically but there is lack of knowledge and accuracy in this field, while relevant numerical equations can hardly be solved.

The experimental part of this thesis consists of different stages and experiments to derive proofs for the theoretical conclusions related to the soil substrate and the water flow. As it can be understood from the results, the system design had certain failures, which were discovered during the experiments and lead to further optimization. Continuation of the experimental work should include observation of plant growth and further exploration of moisture content and its effect on the water flow inside the soil substrate. For the current research, the soil water flow was tested in a short term period, which means that the moisture content slightly changed after the assembling. For further research, the water flow could be tested in long term periods, when the moisture content of the substrate changes significantly.

Further experimenting can reveal more and more positive or negative results, seeking to reach the best integration of the system. There is yet a lot research to be done before finalizing a product that could potentially become a strong architectural element for the future, not only for brick facades but also for any kind of cladding system or wall system in general. Bioreceptivity of building materials and elements is still in its infancy but it has a great potential to offer an entirely new typology of green wall system and incorporate nature into the cities, by transforming building envelopes into green natural environments.

11. Reflection

This project reflects the main goal of my master track, which is to achieve integrated designs for innovative and sustainable buildings. The key to sustainability, in my opinion, is to incorporate nature in the building environment, so that they become integrally connected. Making plants part of masonry walls is one step closer to this vision, while there is a lot more to explore in the research and design field in order to offer similarly oriented proposals.

One conclusion of my research is that bioreceptivity of building materials and products has great potential to offer an entirely new typology of green wall system. This thesis project is one research step towards making our cities green and sustainable.

From the beginning of my master, we focused on defining sustainability and the real aspects to achieve sustainable products and designs. We learned a lot about materials, their performance, design techniques and components and how to combine all these together to propose innovative applications in the built environment.

All this knowledge together with my bachelor experience guided my steps and decisions during the conduction of my thesis. I had to deal with many challenges in various scientific fields in order to propose a strong product that is both sustainable and innovative. Simplicity and functionality were also key aspects to lead the design.

During my research, I came across difficulties, which was also a consequence of the Covid-19 situation. All this uncertainty, which included closure of the faculty for many months had an influence on my thesis steps, especially those related to the experimental research which had to take place in the faculty. Beside these difficulties, together with the help of my mentors, I found a balance and a focus for my research. The experimental part, was more than helpful for me to understand a lot of aspects, in the real field. Even the lack of equipment was useful by leading my creativity to find solutions. Experiments offered this thesis a very creative and realistic point of view. They were full of surprises, both unpleasant and pleasant and they provided my research with very useful results for further improving my product design.

Parallel to my work, I received important feedback from my mentors, which guided me properly and helped me to define the process of my work and deal with certain challenges. We have decided to separate the mentoring meetings into those mostly related to the design and those mostly related to the materials and their performance. So, I received distinguished feedback for those two aspects and this helped for a better organization and clarification of the thesis procedure.

In conclusion, my graduation thesis, has been proven very informative and creative until now. It introduced me to unknown scientific fields and gave me the chance to creatively design and experiment, while also solving occurring problems and dilemmas. Continuation of my project for reaching its final form for the P5 will include further elaboration on the design according to the results from the experimental work. Design elements and details can be refined in order to reflect the proposed improvements which derive by the experimental outcome. Further experiments can be also executed during the time left, in order to refine more certain aspects related to the product performance.

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Appendix A

Plant species and selection

Plant species

1. Asplenium trichomanes
2. Asplenium scolopendrium
3. Chaenorhinum origanifolium
4. Corydalis cheilanthifolia
5. Pseudofumaria alba
6. Campanula portenschlagiana
7. Trachelium caeruleum
8. Sedum album
9. Sedum rupestre 'Angelina'
10. Erinus alpinus
11. Aurinia saxatilis
12. Cymbalaria muralis
13. Antirrhinum majus
14. Erigeron karvinskianus
15. Erysimum cheiri
16. Asplenium ruta-muraria
17. Asplenium adiantum nigrum
18. Parietaria Judaica
19. Dryopteris filix-mas
20. Dryopteris carthusiana
21. Polystichum polyblepharum

Appendix B

Soil technical datasheets

1. BVB UrbanAccap substrate

Productblad BVB UrbanAccap substraat

Aan de basis van de groei

Toepassingsgebied

- Geschikt voor het mogelijk maken van groei van beplanting kademuren, o.a. varens.
  Hydraulisch substraat met capillaire wateropname tot 1,5 m en geschikt voor onder water.

Samenstelling

• Zuurgraad pH (H_2O)	: 6,0 - 7,0		NEN-EN 13037
• Zuurgraad pH (KCL)	: 6,0 - 7,0		NEN-EN 5750
• Droge stof	: > 85	: % gewicht	NEN-EN5754
• Organisch stofgehalte	: 10 - 20	: %-DS	NEN-EN 5754
• Lutum	: 1,0 - 4,0	: %-DS	NEN-EN 5754
• Respiratiesnelheid	: < 5	: mmol O2/kg OS/uur	NEN-EN 16087-1
• Chloridegehalte	: < 350	: mg/l	NEN-EN 13652
Voorraad Voedingselementen			
• Stikstof (N)	: 100 - 300	: mg / 100 gr DS	NEN-EN 13654
• Fosfaat (P2O5)	: 10 - 50	: mg / 100 gr DS	NEN-EN 5793
• Kali (K2O)	: 25 - 100	: mg / 100 gr DS	K-HCl
• Magnesium (MgO)	: > 500	: mg / kg DS	Mg-CaCl

- Vrij van overblijvende onkruiden
- Voldoet aan het Besluit Gebruik Meststoffen

Bij vragen of opmerkingen, neem vrijblijvend contact op met een van onze adviseurs.

2. ACCAP 7120

ACCAP 7120

Muurplantensysteem voor kademuren

Product blad

Product code: ACCAP 7120

Muurplantensysteem ACCAP 7120 stimuleert de groei van de natuurlijke muurflora. Het product is zelf geen groeimedium maar draagt actief bij aan het versneld toegankelijk maken van de muur (kademuur) voor een natuurlijke plantengroei.

Functies:
- Groeiplaats omstandigheden creëren voor natuurlijke beplanting

Toepassing:
Voor nieuwe kade muren waarbij de muur waterdicht is afgeschermd met de kade, de grond achter de muur.

Bestandsdelen:
Muurplantensysteem ACCAP RD bestaat uit 2 halffabricaten welke tijdens verwerking met elkaar vermengd dienen te worden met water, zie verwerkings-voorschriften. Hoogwaardige grondstoffen allen van natuurlijke oorsprong welke op een duurzame manier worden gewonnen en verwerkt.

Technisch support:
Gedetailleerde toelichting en assistentie voor het engineren is beschikbaar. Neemt u voor verdere informatie contact op met een van onze technische medewerkers, mail info@groenekade.nl

ACCAP vulling;

pH(H2O) :	5,5 – 7,0
EC :	< 0,5
Droog gewicht :	350 - 450 kg/m3
Respiratiesnelheid :	< 4 mmol O2/kg.OS/uur
Chloride-gehalte :	< 350 mg/l

ACCAP 7120 (uitgehard product)

Verzadigd gewicht :	875 kg/m3
Max. watercap.:	40 vol-%
Poriënvolume :	60 vol-%
Min. capillaire opstijging :	100 cm
Hechtwaarde :	0,12 N/mm2

GROENE KADE

Zandkant 14, 5845EV Sint Anthonis
www.groenkade.nl
info@groenekade.nl

3. Capillary sand TGS + fiber

Productcertificaat
Cappilairzand TGS + vezel

RAG
Galgeweg 38
2691 MG 's Gravenzande
tel. 0174 - 620360
fax 0174 - 640413
email info@rhp.nl

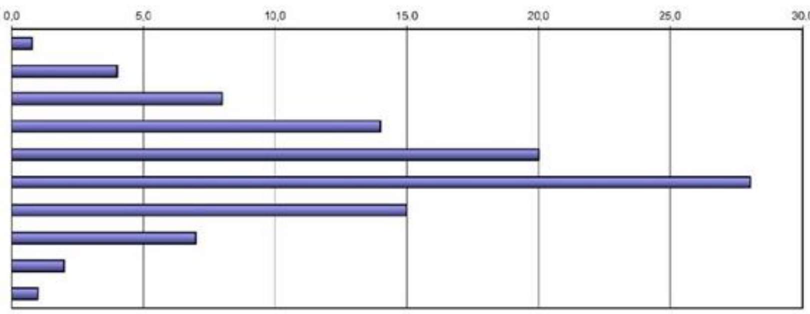
Aanduiding	Cappilairzand TGS + vezel
Datum	15-mrt-18

Doseringsprincipe EN volume

Resultaten berekening	
Bulkgewicht vers/m³	1213
Bulkgewicht droog/m³	1152
% lutum	0,8
% leem	12,8
% organische stof	0,0
EC	0,1
Chloride (mg/l)	43
Koolzure kalk ($CaCO_3$)	0,1

M50	170
D60/D10	4,7

0 - 2 µm	0,8
2 - 16 µm	4,0
16 - 50 µm	8,0
50 - 105 µm	14,0
105 - 150 µm	20,0
150 - 210 µm	28,0
210 - 300 µm	15,0
300 - 420 µm	7,0
420 - 600 µm	2,0
600 - 2000 µm	1,0



4. TGS lower substrate light

Specificatie Berekening
TGS ondersubstraat licht

Heicom
Broekeroordsweg 3b
8095 RM Oldebroek
tel. : 0525-630889
email : info@heicom.nl
www.heicom.nl

Aanduiding	TGS ondersubstraat
Datum	30-apr-21

Resultaten berekening

Dosering op basis van EN volume

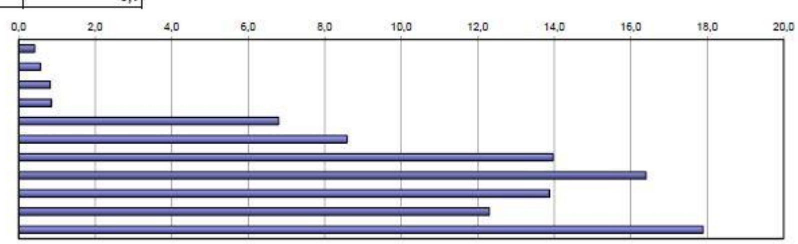
Fysische eigenschappen	
Bulkgewicht vers/m³	991
Bulkgewicht droog/m³	909
% lutum	0,4
% leem	1,8
% organische stof	2,2
Chemische eigenschappen	
EC	0,3
Chloride (mg/l)	26
Koolzure kalk ($CaCO_3$)	0,3

Berekend poriënvolume		
Verdichting	Bulkgewicht	poriënvolume (%)
EN bulkgewicht	991 kg/m³	43
bij 5% verdichting	1043 kg/m³	40
bij 10% verdichting	1101 kg/m³	37
bij 15% verdichting	1166 kg/m³	33

Granulaire eigenschappen

M50	347
D60/D10	3,9

0- 2 µm	0,4
2- 16 µm	0,6
16 - 50 µm	0,8
50 - 63 µm	0,9
63 -125 µm	6,8
125 - 180 µm	8,6
180 - 250 µm	14,0
250 - 355 µm	16,4
355 - 500 µm	13,9
500 - 1000 µm	12,3
1000 -2000 µm	17,9



5. TGS Upper substrate light

Specificatie Berekening
TGS bovensubstraat licht

Heicom
Broekeroordsweg 3b
8095 RM Oldebroek
tel. : 0525-630889
email : info@heicom.nl
www.heicom.nl

Aanduiding	TGS bovensubstraat
Datum	30-apr-21

Resultaten berekening

Dosering op basis van EN volume

Fysische eigenschappen	
Bulkgewicht vers/m³	761
Bulkgewicht droog/m³	630
% lutum	0,5
% leem	1,9
% organische stof	8,1
Chemische eigenschappen	
EC	0,6
Chloride (mg/l)	38
Koolzure kalk ($CaCO_3$)	0,3

Berekend poriënvolume		
Verdichting	**Bulkgewicht**	**poriënvolume (%)**
EN bulkgewicht	761 kg/m³	61
bij 5% verdichting	801 kg/m³	58
bij 10% verdichting	845 kg/m³	56
bij 15% verdichting	895 kg/m³	54

Granulaire eigenschappen

M50	341
D60/D10	3,8

0- 2 µm	0,5
2- 16 µm	0,6
16 - 50 µm	0,8
50 - 63 µm	1,0
63 -125 µm	6,9
125 - 180 µm	8,7
180 - 250 µm	14,4
250 - 355 µm	16,8
355 - 500 µm	14,0
500 - 1000 µm	12,1
1000 -2000 µm	17,3