Design of a pervious concrete quay wall suitable for vascular plant growth

by Marit Meijvogel

TU Delft

Holcim

Front page: Quay wall in Middelburg with maidenhair spleenwort, wall-rue and hart's tongue fern (Maes and van den Dool, 2006)

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by

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Preface

This thesis represents my research on a vegetated green quay wall made with pervious concrete. It is written in the frame of finishing my master Structural Engineering at the TU Delft, Netherlands. This thesis would not have ended up the way it does without the support of several people. First of all, a big thank you towards Prof. dr. Henk Jonkers and Dr. ir. Marc Ottele for their great support, discussions and critique. I have appreciated your approachability and helpfullness a lot during our many meetings. I also want to thank Bart van Zwicht and Jan Wagner from Holcim for making this research possible and for guiding me through the process, providing support and for provision of resources. Without them, this project would not have been possible. From the committee, I would also like to thank Dr. ir. Roel Schipper, who joined the committee near the end of this research.

Outside of the committee there are also other mentions that I want to share. First of all, the technical staff from the TU Delft and Holcim. Sjaak Vermeij (Holcim), Pascal Meerenburg (Holcim), Jack Verlaar (Holcim), Teun Noordam (Holcim), Maiko van Leeuwen (TU Delft) and Ton Blom (TU Delft) all helped me with the experimental equipment and explaining of the operation of the equipment. A special thank you to Ron Penners (TU Delft) for all the times I could use the sieving machine despite of the annoying noise this caused in his office. Furthermore, I was surprised by the willingness of all people I approached to help in whatever way possible, so thank you Max Veeger, Erwin van Herweijnen and Savina Taouki for our conversations and for answering my questions. The experiments could not have been done without the resources, for which I want to express my gratitude to Mark Offerman from H&B Grondstoffen and Stefan Dekker from BVB Landscaping.

Of course the support from people not directly involved can be just as important. Thank you mom and dad, for your support during my thesis and during the other years of my study. You have always done everything inside your power and beyond to help me and I am so happy to have such loving parents. Also a big thank you to my sister, who provided some sharp comments on my report, but who most of all showed that although it sometimes seems impossible, verything works out in the end. As promised a special thank you to Max and Schelto Blanken who helped with my experiments, but most importantly enlightened my moods during long study days. There are many more friends which I will not all mention by name, but I want to thank them for encouraging me and supporting me. I really appreciate you all.

M.J. Meijvogel
Delft, May 2023

Summary

Due to ageing of the bricks and joints of traditional masonry quay walls, plants can develop on the quays, which positively affects urban biodiversity. Apart from improving the biodiversity in cities, vegetated quay walls improve amongst others the urban heat island effect and contribute to citizens' well-being. When replacing these quay walls, this valuable ecosystem is lost, since modern quay walls are usually not suitable for vegetation. The goal was thus to design a modern-day quay wall made with a substrate layer that can host ecologically valued quay wall species. In this way, biodiversity is not permanently lost when replacement of old quay walls is unavoidable. Pervious concrete was chosen for its high interconnected porosity, which combined with a soil mixture in the pores, forms a suitable growing layer for plants. Minimal maintenance was demanded, meaning that the quay wall should be self-sustaining. The research investigated which types of vascular plants are dependent on quay wall ecosystems in the Netherlands and determined which (wall) characteristics allow the growth of those ecologically valued species. These findings were used to determine the ecological requirements that together with the technical requirements formed the framework for the design of the quay wall.

The ecological requirements set boundaries for moisture availability, alkalinity, nutrient availability, surface roughness and root ability as these are the factors that primarily influence the establishment of plants on walls. Due to the use of a homogeneous fraction of coarse aggregates and the limited cement paste content, the interconnected porosity of pervious concrete is high. Since the interconnected void ratio is linked to the surface roughness and the root ability, pervious concrete is ideal for creating a substrate for wall plants. An appropriate alkalinity level is reached due to fast carbonation of pervious concrete and nutrient availability is guaranteed by inserting a soil mixture in the macro-pores of the pervious layer. Therefore, the most challenging requirement was the moisture availability, especially as the design had to be self-sustaining, so the need for manual irrigation was reduced as much as possible. Moisture availability was thus dependent on natural water supply and water retention in the substrate layer. Since literature on water retention in pervious concrete for quay wall applications was not available, this property was investigated and optimized in the experimental part of this thesis. For the optimization of the substrate layer, no additional material use is required. Therefore, this adaption is simple, cost-effective and durable.

The experimental research used two types of coarse aggregates, which were lava stone aggregate and pumice stone aggregate, in combination with different water-to-cement ratios (WCR) in the range of 0.4 to 0.8, to improve the water retention of pervious concrete. The composition of the mix designs is given in Table 1. All mix designs of the first series under performed with respect to strength and durability, as the 28-day compressive strengths were below 1 MPa and complete failure occurred within 14 freeze-thaw (FT) cycles. This showed that a too low cement content, which resulted in a thin cement paste coating and a high interconnected void ratio, caused insufficient strength development and low durability. The aggregate-to-cement paste volume ratio (ACR) was increased from a value of 4 (and 6 for the mix designs with pumice stone aggregate due to a false assumption for the density and the water absorption of this aggregate type) in the first series to a value of 2 in the second series, so the cement paste volume was doubled. This positively affected the strength and durability properties. However, only one of the three tested mix designs of the second series developed the intended compressive strength of 6 MPa after 28 days of curing, which was mix design C2.1 as is shown in Table 2. This mix design also had excellent freeze-thaw resistance as the mass loss was only 2-8% after 28 cycles.

From the results it was concluded that the use of a WCR below 0.6 is recommended with a minimum WCR of 0.4. Although the water absorption capacity was slightly increased when a WCR of 0.6 or higher was used, the technical requirements for strength and durability were not met by these mix designs. The WCR was initially adjusted as it was believed that the WCR influenced the water absorption of the aggregate material. However, as the test results showed that the amount of water absorbed by the aggregate material was independent of the WCR (within the tested range), pervious concrete can

Table 1: Compositions of the mix designs tested in the first and the second series of the experimental part

		Aggregate Type [-]	Aggregate Fraction [mm]	WCR [-]	ACR [-]
First series	C1.1	Pumice stone	8 / 11.2	0.6	6
	C1.2	Pumice stone	11.2 / 16	0.8	6
	C1.3	Lava stone	8 / 11.2	0.8	4
	C1.4	Lava stone	11.2 / 16	0.8	4
Second series	C2.1	Lava stone	8 / 16	0.4	2
	C2.2	Lava stone	8 / 16	0.6	2
	C2.3	Lava stone	8 / 16	0.8	2

Table 2: Performance* of the mix designs that are tested in the first and the second series of the experimental part

		Void ratio	Water absorption	Compressive strength	freeze-thaw resistance
First series	C1.1	green	yellow	red	red
	C1.2	green	yellow	red	red
	C1.3	green	red	red	red
	C1.4	green	red	red	red
Second series	C2.1	green	red	green	green
	C2.2	green	red	yellow	yellow
	C2.3	green	red	red	red

* Green represents good performance, yellow represents questionable performance and red represents insufficient performance

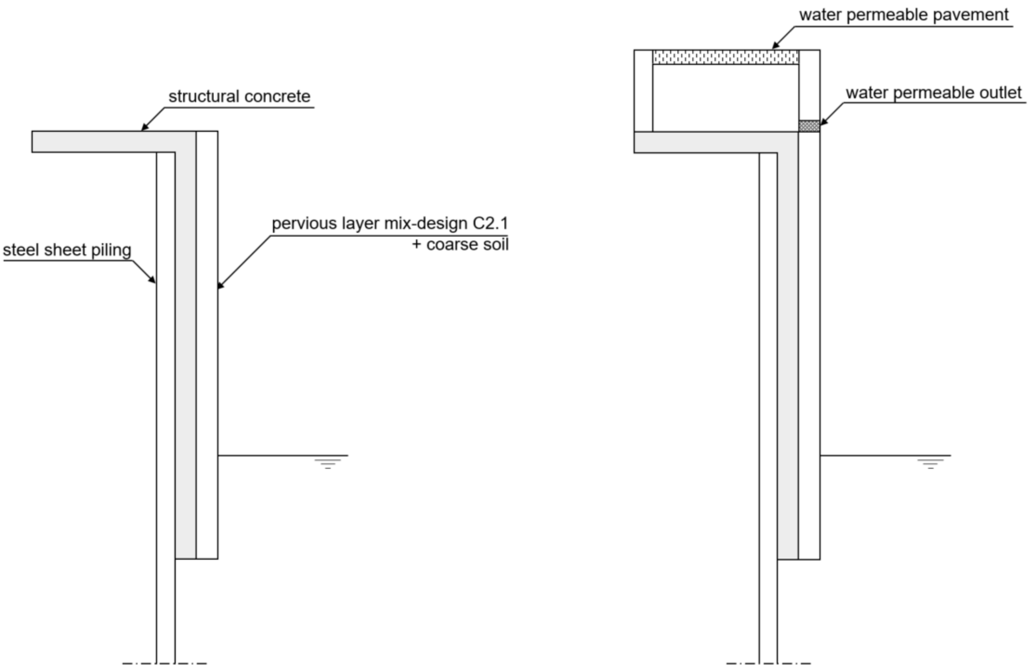
be optimized by adjusting the aggregate type for a WCR between 0.4 and 0.6. As the cement paste content in pervious concrete is small, more could be gained by optimizing the water absorption in the aggregate material instead of optimizing the water absorption in the cement paste layer.

The raw pumice stone that is used as aggregate absorbed 3.5 times more water than lava stone aggregate and the results of the first series showed that the use of pumice stone enhanced the water absorption of pervious concrete with a factor of approximately 2.5. Despite this clear increase, pumice stone was not included in the second series as the freeze-thaw results of the first series were unacceptable. However, increasing the cement content and reducing the WCR to a value of 0.4 improved the freeze-thaw resistance of the samples with lava stone to an acceptable level. It is therefore worthwhile to check if a further optimized mix design with pumice stone in combination with a WCR of 0.4 and an ACR of 2 could also meet the strength and durability demands.

The addition of a soil mixture to the macro-pores increased both the maximum water absorption capacity and the capillary suction. In practice this capillary water absorption is important for the distribution of water within the substrate layer as the upper part of the substrate layer is mostly exposed to rainwater from one side. Additionally, the lower part of the quay wall is immersed in the canal water as can be seen in Figure 1, so capillary absorption transports canal water to the substrate layer. To which extent the water can rise in the substrate layer by insertion of soil in the pores was not determined and should be investigated in future research.

The experimental research proved that water retention in pervious concrete in combination with soil was possible and was promising for partial fulfilment of the moisture requirement. However, due to high evapotranspiration rates in practical situations, the substrate layer from the quay wall in Figure 1a was drying out too fast despite of the water absorption capacity of mix design C2.1 in combination with soil. The maximum water absorption capacity of the substrate layer was namely 265.1 g/L while the losses due to evapotranspiration were on average 34 g/L/day. This meant that the substrate layer dried out within 8 days during a dry period without rain. In this situation the capillary water absorption from the canal was ignored as it was unknown to what extent vertical water transport can occur.

Combining the substrate layer with a water reservoir in the capping stone could assure a more constant water supply to the substrate layer, which was beneficial for the water content of that layer. A sketch of this design can be found in Figure 1b. The inflow and outflow of water from the reservoir and the substrate layer were modelled based on the precipitation and evapotranspiration data of the KNMI to determine the moisture content of the substrate layer. The current inflow-outflow model showed that although the water content of the substrate layer was in general higher for the situation with a reservoir, complete dry-out of the substrate layer still exceeded the maximum permitted period of two weeks. The substrate layer would have dried out for approximately one month during the summer of 2018. This finding suggested that the current design does not fulfil the moisture requirement and was thus, without intermediate manual irrigation, not suitable for hosting ecologically valued species. However, when the moisture requirement was not fulfilled completely, this did not mean that no vegetation could occur on the quay wall. The moisture requirement was namely not a strict requirement, as quantitative data on the moisture preferences of the selected species was not available. The requirement was thus based on assumptions. Additionally, the inflow-outflow model was sensitive to the inaccuracies of the input parameters and the model was only calculating the moisture content based on precipitation and evapotranspiration data of the past 5 years. This led to the belief that the current design will presumably be able to host the preferred species to a certain extent. To improve the moisture conditions on the quay wall, a minimum form of maintenance could be implemented to improve the moisture conditions in the substrate layer during long dry periods. Furthermore, if proven possible, the water absorption capacity of the substrate layer from the design of Figure 1 could be improved by (partial) replacement of lava stone aggregate with pumice stone aggregate.



(a) Simplest design (b) Design with reservoir

Figure 1: Sketches of the design variants of the quay wall

More accurate modelling is needed to determine the daily moisture content of the substrate layer with higher reliability. Capillary water absorption and the relation between the moisture content and the evapotranspiration rate should be considered to improve the model. To include those processes, more testing data is needed to predict the capillary water absorption behaviour and the evapotranspiration behaviour of the substrate layer for different moisture contents. Furthermore, the evaporation from the reservoir might be overestimated and more reliable data should be used to predict the evaporation rate from the reservoir. Apart from improving the model, an alternative solution strategy in the direction of reducing the losses due to evaporation could be investigated to improve the current design of the quay wall.

Contents

Abbreviations

ACR	Aggregate-to-cement paste volume ratio
CBR	California Bearing Ratio
FT	Freeze-thaw
KNMI	Koninklijk Nederlands Meteorologisch Instituut (Royal Dutch Meteorological Institute)
MCA	Multi-criteria analysis
RH	Relative humidity
T	Temperature
WCR	Water-to-cement mass ratio

1 Introduction

1.1. Bio-receptive building material

Many scientific papers mention the usefulness of vegetation on vertical surfaces within urban areas, so called green façades and living wall systems. These systems adapt vertical building surfaces in order to make plant growth possible. Green façades and living wall systems reduce the number of air pollutants, retain stormwater, increase biodiversity, mitigate the urban heat island effect and work as an alternative insulation material (Moreira-Zambrano and Moreno-Rangel, 2020) (Dimitrijevic Jovanovic et al., 2018). Besides these benefits, the added greenery positively affects citizens' social and psychological well-being (Zia et al., 2013). The previously mentioned techniques use external systems, which are added to the façade. The downside of those techniques is the need for additional material use, which results in high (environmental) costs. Furthermore, a misalignment in lifespan between the exterior system and the façade results in the need for replacement during service life (Riley et al., 2019). Another disadvantage is the fact that traditional systems are often maintenance intensive. Irrigation systems are included in the design of traditional systems and regular check-ups are needed for pruning of the plants (Hemalatha, Ranjit Raj, et al., 2021).

Because of the drawbacks of green façades and living wall systems, the use of bio-receptive materials as building materials is investigated. This way, the vegetated wall forms an integrated part of the construction. Two groups of bio-receptive materials can be distinguished. The first group focuses on colonization by microorganisms and non-vascular plants. A natural example is the mosses that grow on old concrete infrastructural projects. The second group is the bio-receptive material stimulating vascular plant growth. For example, the natural phenomenon that plants like ferns grow on decayed masonry quay walls.

Inspired by the vascular plant growth in cracks of old walls, a two-layered concrete panel is designed by Holcim Nederland. The design is derived from the experiments done by Riley et al. (2019). The technique is also mentioned by Ottelé et al. (2011) and is referred to as "bloemetjes beton". The concrete panel consists of a structural layer and a pervious concrete layer in which soil is added as a growing medium for vascular plants. Pervious concrete is a subgroup of porous concrete, which is distinguished by its interconnected pore system. The pervious concrete layer consists of coarse aggregate and cement paste, which ensures an appropriate ratio of voids to concrete. After casting and hardening, the voids are filled with soil. The rough surface, with interconnected void spaces, allows for the accumulation of water and nutrients. It also provides space for roots, which should make successful establishment of vascular plants possible. The panel can be applied in several applications, such as green façades, noise barriers along highways, or quay wall coverings.

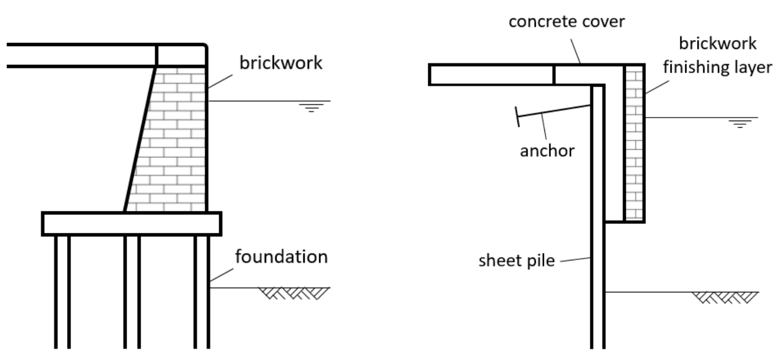
1.2. Problem Statement

Cities in the Netherlands currently face the problem that most of the quay walls are over a century old and have to be replaced (Amsterdam, 2022). Next to the logistical challenges of this major replacement project, the disappearance of the characteristic wall environment for plants and animals is a danger for the ecology. A certain level of decay of a wall is namely needed to change its properties and make it suitable for quay wall plants. This makes the establishment of flora and fauna on quay walls a time consuming process that takes decades. Therefore, it is undesirable to replace the quay walls with new materials that are not (directly) suitable for the growth of plants. The use of the pervious concrete as bio-receptive material stimulating vascular plant growth in the application of a quay wall is a promising solution, to prevent the disappearance of quay wall ecosystems.

The time needed for the ageing of building materials to make them suitable for vegetation is not the only obstacle. Modern technologies for constructing quay walls differ from traditional brick quay wall systems as is visualised in Figure 1.1. Nowadays, the retaining function is often fulfilled by a steel sheet piling. This layer is covered by a concrete element with an appealing finishing layer, as the appearance of the steel sheet construction is not attractive. In this situation, the finishing layer is not in direct contact with the ground and the groundwater. This means that the finishing layer becomes completely dry on hot days, in contrast to the traditional brick quay wall that is kept moisturized by the groundwater in the soil behind the wall. This dry and hot environment of modern quay walls makes developing a habitat for quay wall plants extremely difficult. As regular irrigation of a quay wall is labour intensive and cost ineffective, the quay wall should be self-sustaining. This requirement should be addressed when considering pervious concrete for the construction of quay walls.

Previous research tested bio-receptive pervious concrete panels for vascular plants that are irrigated regularly. This indicates that a low maintenance material is a research gap in this subject area (Hemalatha, Ranjit Raj, et al., 2021) (Riley et al., 2019) (Ottelé et al., 2011). Pervious concrete is not tested in applications without irrigation, but other finishing layers stimulating plant growth have recently been tested on quay walls in the Netherlands. The GreenQuays project in Breda (Dijkhuis et al., 2021), the green quay walls at the Houthaven in Amsterdam (Denters et al., 2019) and the Quay Wall Garden Delft project by the Faculty of Architecture (Mulder, 2022) all use a vegetated masonry finishing layer attached to a constructive concrete layer. These three reference projects are reviewed in paragraph 2.1 to determine which factors contribute to successful establishment of vegetation on quay walls. One of the conclusions of these investigations is that inserting a capillary substrate layer between the constructive concrete layer and the finishing layer, is of key importance for successful germination of seeds and growth of plants. This conclusion shows that implementation of a bio-receptive finishing layer in modern day quay wall constructions is possible, but only when the design is adjusted to ensure a moist finishing layer.

An overview of the alternatives that are considered for the design of a self-sustaining quay wall is given in Figure 1.2. The first alternative is the modification of the material of the finishing layer to increase the water retention properties of that layer. A second option is the addition of a water reservoir in the capping stone, which distributes water over the quay wall in dry periods ensuring a moist finishing layer. The third and last alternative is the modification of the system making use of capillary materials to vertically transport water from the canal to the quay wall. As the first alternative can be implemented



(a) Traditional masonry system (b) Modern steel sheet piling system

Figure 1.1: Two types of quay wall systems commonly used in the Netherlands

without the use of additional materials, this adaption is simple, cost-effective and durable. Therefore, this thesis is primarily focusing on adjusting the pervious concrete mix design and quantifying the effect of those adjustments on the (water retaining) properties. After quantification, the potential of material modifications for accomplishing a self-sustaining quay wall is discussed. Additionally, a combination of the material modification with one of the system modifications is considered.

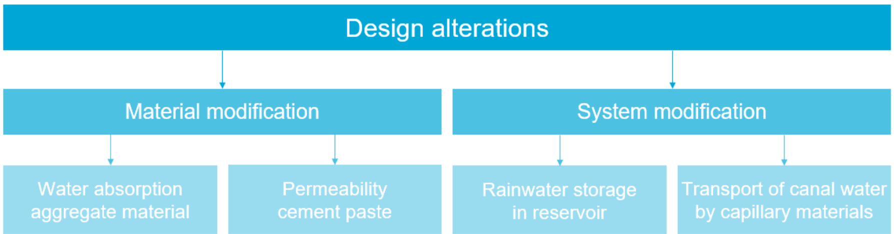


Figure 1.2: Different types of design alterations that are considered during this investigation

The layered concrete system should be designed in such a way that it resembles the structural and ecological properties of a decayed traditional quay wall immediately after installation. In this way, the new quay wall enables the growth of native plants and stimulates natural succession of vegetation. Before considering the previously mentioned design alterations, the ecosystem that currently exists on quay walls is analyzed to determine which properties of a quay wall are vital for fulfilling its ecological function. Apart from the humidity level, which is already indicated as a governing factor, properties such as a specific pH-value, nutrient level, porosity and surface roughness, should be incorporated in the design of a vegetated quay wall. Next to the preconditions that are defined by the preferred ecosystem, other requirements should be realized when designing a vegetated concrete quay wall. Those requirements follow from the technical specifications that are established based on the performance and functional requirements. The structural layer, to which the finishing layer is attached, is the most important regarding strength and stiffness. The concrete mixture of this part should be produced according to the project specifications and must comply with national and European standards (Eurocodes). The pervious concrete layer is attached to the structural layer and does not require the same strength and stiffness characteristics as the structural layer.

1.3. Objective and scope

This thesis will mostly focus on the pervious layer, but an appropriate connection between the layers should be considered to ensure its function. The pervious layer must fulfil requirements regarding minimum compressive strength, environmental conditions, and durability. Both the requirements based on the ecological function and the technical specification are established by literature research. After determining if the requirements can be fulfilled on material level, the focus of the thesis is widened to the design of the self-sustaining quay wall on system level. The quay wall element should be producible in the factory of Holcim Bouw & Infra B.V. in the Netherlands. However, this requirement should not limit the initial process of design.

The quay wall covering element consists of a horizontal and a vertical part as can be seen in Figure 1.1b. A maximum height of two meters is set as a boundary condition for the vertical part. In addition to this distinction, the vertical part can be further divided into three areas: the part that remains entirely underwater, the part around water level, which has a dry-wet environment, and the top part, which is always above the water surface. In total, there are thus four areas with different conditions that support different species. To specify the goal of this research, the design of the quay wall covering is focused on the desired ecosystem of the zone above the water surface. Designs targeting the ecology of the underwater zone or other (e.g. marine) environments are not part of the scope of the present research. Furthermore, the horizontal part of the quay wall covering should be designed with a primary focus on the supply and support of the vertical part. The natural habitat of a quay wall is dependent on the location of the quay wall, the orientation, and other factors. The design should be specifically tailored for a certain location and environment. To define the scope, the research is limited to designing an element suitable for a quay wall covering in a freshwater canal in a city in the Netherlands.

1.4. Research questions

This research proposes a layered concrete system that fulfils the requirements and is an appropriate alternative for current techniques in this specific application. Since the structural layer is not related to the bio-receptivity of the element, this thesis will focus mainly on the pervious layer. The accompanying research question is drafted as follows:

"How can the build-up and mix design of the layered concrete element, with the focus on the pervious layer, be optimized to obtain a self-sustaining quay wall system that imitates the ecological function of a traditional masonry quay wall in a freshwater canal of a Dutch city whilst fulfilling the technical requirements?"

The essence of this question is rephrased to the following question that clearly describes the goal of the investigation: *"How can a self-sustaining vegetated pervious concrete quay wall be designed?"*

To answer this research question, the following sub-questions are proposed:

SQ1: Which type of vascular plant species are specific for the ecosystem on a traditional masonry quay wall and what (wall) characteristics allow the growth of those ecologically valued species?

SQ2: How can the pervious concrete mix design be adjusted to control the previously indicated characteristics on material level?

SQ3: How can the design of the quay wall be adjusted to improve the water characteristics of the system?

1.5. Approach and reading guide

This thesis is divided in three parts. The first part is about the general design properties of the quay wall element. It includes an evaluation of similar projects and the lessons that can be learned from those projects. The third chapter sets the framework of the design by determining the ecological and technical requirements through literature research. Ecological requirements are set for the moisture content, alkalinity, nutrient availability, surface roughness and root ability of the material. The technical specifications are restricted to a minimum compressive strength and the durability of the pervious layer and the suitability to general environmental conditions. The last chapter of part I will relate the properties of pervious concrete to the previously set requirements.

Part II of this thesis concentrates on the material modification of the pervious layer to improve the water retaining characteristics. The moisture requirement is namely considered as the biggest challenge for the vegetated quay wall as it should be self-sustaining which is not yet accomplished in previous research. Experiments are conducted to determine the effect of multiple design parameters on the water retention properties of the pervious concrete. Additionally, the effect of the parameters on the strength and durability is evaluated. Experiments are performed on the raw aggregate, the cement paste, the cement mortar and the pervious concrete. The results are included in chapter 6.

As the alteration of the mix design is not sufficient to fulfil the water retention requirement of the quay wall on material level, the combination of the material modification with a system modification is considered. For this the water income and outcome of the complete system is analysed and system modifications are proposed. A multi-criteria analysis is done to determine which system modification should be included in the design. This water flows for this design variant are modelled to determine if the design variant can fulfil the ecological requirement concerning the water retention properties of the quay wall.

A visualisation of the report structure can be seen in Figure 1.3. At the end, the report is concluded with a discussion, a conclusion and with recommendations for further research.

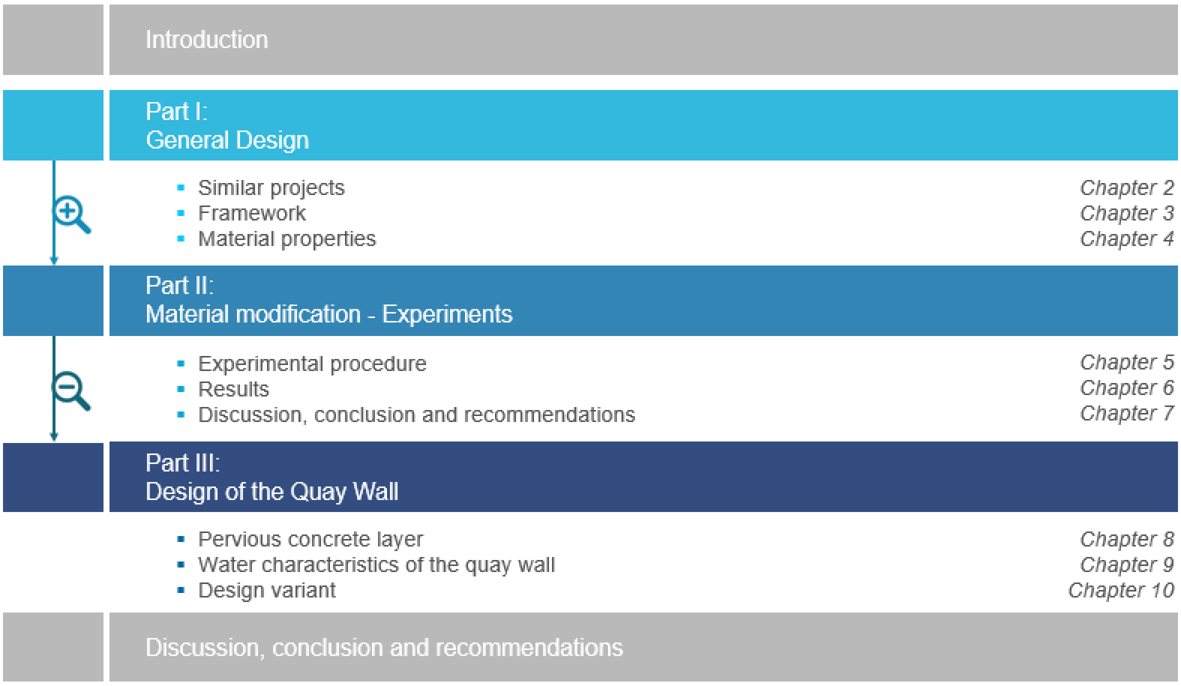


Figure 1.3: Structure of the report consisting of different parts.

I

General Design Properties

2
Reference projects

In literature, bio-receptive concrete is mentioned in many investigations. However, most of those results focus on moss growth on concrete. Since this thesis focuses on highly pervious concrete suitable for the growth of vascular plants, much of the research is not specifically applicable. Vegetated pervious concrete in the application of a self-sustaining quay wall is not encountered in literature. The information from multiple research papers should thus be combined to understand and predict the behaviour of pervious concrete in this application.

2.1. Vegetated masonry quay wall

Three recent research projects in the Netherlands focused on applying a quay wall suitable for vegetation, namely in Amsterdam, Breda and Delft. Those projects are evaluated and compared to conclude which factors are important for designing a vegetated quay wall.

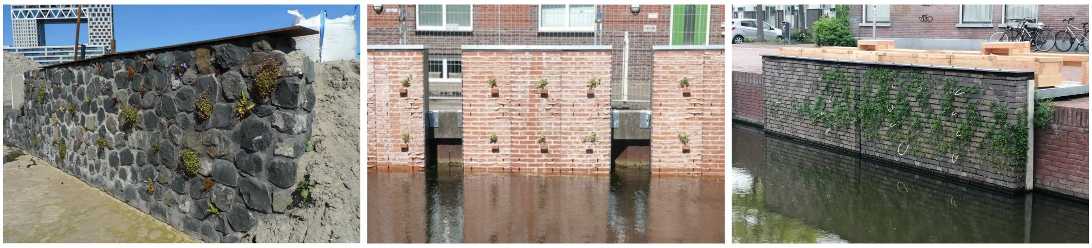
2.1.1. Vegetated quays Houthaven Amsterdam

The municipality of Amsterdam initiated a pilot project that experimented with a bio-receptive quay wall for vegetation (Denters et al., 2019). The project, located at the Houthaven in Amsterdam, consisted of a concrete wall covered with a capillary cloth and a system made of crates filled with substrate. A masonry basalt layer was attached to the crate system. Figure 2.1a presents a picture of the initial set-up.

Three types of panels were tested. The difference between the panels was the use of different types of substrates. One substrate of the company BVB and two substrates of the company TGS were tested. To prevent inaccurate capillary moisture measurements, rainwater could not access the system from above. However, for the final design, infiltration of rainwater was recommended by Denters et al. (2019). Plants were added to the mortar of the basalt layer during the bricklaying on predetermined spots on the wall. The roots of the plants where in the substrate layer behind the masonry. A sensor measured the moisture tension at a certain height in all three panels.

After a half year, the vitality of the initial installed plants was good, namely a vitality of 70%. On the lower part of the panels, the average vitality was even better, with a vitality of 90%. However, no new seedlings were seen. This might be caused by the testing period, which was from November till May, so mostly outside the growing season, but it was probably also since the mortar that was used did not allow germination of seeds in the first years after installation.

The BVB substrate was recommended since this substrate reaches a capillary height of 1.5 meters in contrast to the other two substrates which reach lower heights. The use of crates in-between the concrete and the masonry layer was discouraged. Furthermore, capillary cloth was recommended to prevent washout of the substrate through the open joints.



(a) Houthaven Amsterdam (b) GreenQuays Breda (c) Quay Wall Garden Delft

Figure 2.1: Pictures of test panels of vegetated quay wall reference projects in the Netherlands

2.1.2. GreenQuays Breda

The second research is from the organization GreenQuays, a collaboration initiated by the municipality of Breda, which invests the innovative Nature Inclusive Quay technology. The final results of the research are published by Mulder et al. (2023). This research is based on the same application so the problems that were faced are similar, but the proposed technology, a bio-receptive brick masonry quay wall covering, differs from the solution that is at the basis of this thesis, namely the bio-receptive pervious concrete covering.

In Breda ten panels were tested. Five panels were oriented to the north and five panels were oriented to the south. All panels consisted of three vertical strips. One of the three strips had a substrate layer behind the brick masonry layer. The other two strips were made of different masonry bonds (half-brick and one-brick), both without a substrate layer. A soft-mud moulded brick with frog with a water absorption capacity of 450 g/L was used for all panels (Lubelli et al., 2021). Five different types of mortar were tested and the water absorption capacity of the bedding mortar of most panels was 75 g/L. Plants were added in open joints and seeds were glued to the joints. Moisture measurements were done on the mortars and the bricks on two levels in every vertical strip. Temperature measurements were done with a thermal imaging camera. The test set-up directly after installation is shown in Figure 2.1b.

It was concluded that the vertical strips with a substrate layer performed better than the strips without a substrate layer. The added plants only survived on the strips with substrate layer and the seeds germinated faster and better on those strips. The moisture and temperature measurements confirmed that the strips with substrate layer are moister and have a lower temperature than the strips without substrate layer. The temperature difference could rise to approximately 7 degrees (Dijkhuis et al., 2021). Furthermore, the panels in the shadow performed better than the panels in the sun. The planted vegetation lived longer in the shadow and more seedlings lived on the panels in the shadow. Lastly it was concluded that open joints strongly contribute to the establishment of plants.

The approximate water retention capacity of the masonry finishing layer is derived based on the absorption capacity of the bricks and the mortar. Assuming that the finishing layer consisted for 80% of bricks and for 20% of mortar, the water absorption capacity of the finishing layer was 375 g/L. The left and right strip were made without substrate layer and have a thickness of 100 mm and 210 mm, respectively. The water absorption capacity is thus 375 g/m^2 and 787.5 g/m^2, respectively. As it is known that the panels without substrate layer could not host plant species to a satisfactory extent, it is known that the water absorption capacity of the substrate layer should be higher than this value when a similar design without substrate layer is made.

2.1.3. Quay Wall Garden Delft

The Quay Wall Garden project in Delft of the Faculty of Architecture is a follow-up on the project in Breda. This currently running project investigates the possibility of stacking bricks without cement mortar to promote plant growth in the open joints filled with substrate.

Two testing panels are tested: The first with a capillary substrate layer of 55 millimeters behind the masonry layer and the second with a capillary substrate layer of 110 millimeters. The left side of each panel allows rain water flow from the city surface to the quay wall. Infiltration of rainwater from above is prevented for the right side of the panel. This panel is thus only watered by direct precipitation and capillary water absorption from the canal. In the joints a potting soil with seeds is bound with a biological adhesive. In time this material will most likely be replaced by other organic material, but it is important for the germination of the first seeds. With sensors the moisture content in the joints is measured at different heights in the left and the right part of each panel. The project started in April 2022, so no results have been published yet. However, the project leaders Koen Mulder and Max Veeger were contacted to obtain more information on the project and the measurements that were done up till this moment. In Figure 2.1c the first seedlings on the quay wall a month after installation can be seen.

Three months after the installation of the prototype the results are promising. On both panels plants were growing. Only on the upper part of the testing panel with a 55 millimeter substrate layer where rainwater infiltration was prevented, no vegetation was seen. This difference between the left and the right side of the panel was not seen on the quay wall with a 110 millimeter substrate layer. This indicated that the moisture content and the capillary rise height, may be depended on the thickness of the substrate layer.

2.1.4. Conclusion

The researches presented in this paragraph use different techniques to create the green quay wall, but the application as quay wall in a Dutch city canal is similar. In Table 2.1 an overview of the test set-ups in Amsterdam, Breda and Delft is given. The lessons learned from the previously mentioned research projects, can stimulate the development of the pervious concrete vegetated quay wall.

Table 2.1: Overview of the test set-ups of the vegetated quay wall projects in Amsterdam (Denters et al., 2019), Breda (Mulder et al., 2023) and Delft (Mulder, 2022

	Houthaven Amsterdam	GreenQuays Breda	Quay Wall Garden Delft
Outer layer	Basalt masonry	Brick masonry	Dry-stack brick masonry
Substrate outer layer	-	A plant friendly mortar used on top of the constructive mortar	Potting soil with a biological adhesive
Water bearing layer	Yes, capillary substrate	Yes, capillary substrate	Yes, capillary substrate
Outflow prevention of water bearing layer	Capillary cloth	Unknown	Burlap
Construction in cavity	Crate system and anchor ties	Anchor ties	Anchor ties
Rainwater inflow	Prevented	Enabled	Partly enabled
Planting method	Cultivated plants	Cultivated plants and seeds	Seeds
Testing period	November 2018 – May 2019	April 2020 – June 2022	April 2022 - Ongoing

i. The addition of a capillary substrate layer behind the finishing layer appears to be important for the successful germination of seeds and growth of plants.

This statement is confirmed by the test set-up in Breda, where a design with a substrate layer is compared to a design without a substrate layer. In Delft the results also indicate that a proper working substrate layer positively influences the installation of vegetation on the quay wall over the whole height. The test panels used in Amsterdam are all made with a substrate layer. The plant vitality is higher in the lower part of the wall than in the upper part. With a correctly functioning capillary substrate, the plant growth in the upper part will probably improve. The test set-ups in Breda and Delft proved that the cavity can be filled with substrate without the use of an additional crate system. In the tests in Amsterdam a crate system is added to the cavity, but after the pilot project a design without a crate system is recommended. Washout of the substrate through the open joints should be prevented. In Amsterdam this is done with a capillary cloth. In Delft burlap is placed behind the open joints located under and around the water surface to prevent washout.

Because of this conclusion, adaptions to improve the water retention in the two-layered pervious concrete quay wall are studied in this thesis. The use of an in between substrate layer, which is promising in the masonry quay walls, might not be the most suitable modification for a two-layered pervious concrete element. The current production of this two-layered element does not allow the formation of a cavity in between the two layers. Adjustment of the production process is needed, when a cavity is demanded, but this might result in an uneconomical design which disregards the benefits of the two-layered pervious concrete element. Other adjustments are thus considered as well and are subdivided in material modifications and system modifications.

ii. Open joints strongly contribute to the establishment of plants and the insertion of a potting soil in the open joints is beneficial for the germination of seeds.

The importance of open joints for the establishment opportunities is observed in the testing set-up in Breda. Based on this conclusion the test set-up in Delft is made with only open joints, which shows positive results in terms of vegetation. In Amsterdam no open joints are included in the pilot project and no vegetation is seen in the joints. This observation suggests that there is a correlation between the open joints and the establishment of plants. The insertion of potting soil with seeds in the open joints in the test panels in Delft, shows positive results. In Breda no soil is added to the open joints, but the test panel that scored best in regard to vegetation, is the panel that used a constructive mortar and a plant mortar on top of this. The plant mortar degrades fast, leaving a notch with potting soil, which resembles the situation where potting soil is applied in open joints.

As pervious concrete consists of a lot of ”open joints” due to its high porosity, the establishment opportunities of vegetation are expected to be good for this type of finishing layer. A soil mixture is added to the pores of the pervious concrete in the final design, due to the positive experiences with insertion of potting soil in open joints.

iii. Adding seeds has a positive effect on the establishment of plants.

In Breda and Delft seeds are applied in and on the joints of the quay wall. Both tests show a positive development of seedlings. In Amsterdam no seeds are applied and no new plants are observed. The cultivated plants that are added at the start of the experiment in the test set-ups in Breda and Amsterdam partly survived. However, due to the success of the addition of seeds, the incorporation of cultivated plants is only recommended if the quay wall has to be vegetated from the beginning.

As the available time for this thesis, does not allow tests including vegetation, the addition of seeds is not included in the research. However, the recommendation for the final design is to add seeds to the soil mixture that is added to the pores of the pervious concrete.

iv. The inflow of rainwater from above has a positive effect on the vegetation on the upper part of the quay wall.

This statement is confirmed by the tests done in Delft, where a clear difference is seen between the panels with and without rainwater inflow when a capillary substrate of 55 millimeters is used. For experimental reasons the inflow of water is prevented in the trial set-up in Amsterdam. After some months a clear difference could be distinguished between the vitality of the vegetation on the top part and on the bottom part of the quay wall. Inflow of rainwater from above might have improved the vitality of the vegetation on the top part, resulting in an equally distributed vitality over the whole quay wall.

This conclusion indicates that rainwater should be used to moisturize the finishing layer. The capping stone should thus be designed in such a way, that rainwater from city surfaces can flow to the finishing layer. Additionally, a reservoir could be added to the capping stone to store the incoming rainwater and distribute the rainwater evenly.

2.2. Vascular plants on pervious concrete

There are methods under development for creating a new type of living wall for greening facades. The following three documents focus on the possibility of creating a vegetated wall that is integrated with the building structure by testing a concrete wall element that houses plants due to its pervious structure.

2.2.1. Panels designed by Ottelé et al. (2011)

The phenomenon of creating a green wall with a pervious concrete specimen was new at the time Ottelé et al. (2011) invested a layered pervious concrete element. The success of plant growth on the testing blocks was investigated by adding plants and a soil mixture to the pervious layer and monitoring the development of the plants regularly over four months. Furthermore, the pH-value of the soil mixture was measured to determine the change in pH over time due to the contact with pervious concrete.

After three months, the pH of the soil increased from 7.2 to 9.2 due to contact with the highly alkaline pervious concrete. Despite of the change in pH, some plant species such as Cymbalaria muralis, Asplenium trichomanes and Sedum survived.

(a) by Ottelé et al. (b) by Riley et al. (c) by Hemalatha, Ranjit Raj, et al.

Figure 2.2: Pictures of test samples of vegetated pervious concrete tested in previous research

2.2.2. Panels designed by Riley et al. (2019)

Riley et al. (2019) investigated the possibility to create a layered vegetated concrete element in several steps. The goal was to produce a product that allowed the growth of plants from seed. For this purpose, several concrete mix designs and soil mixes were tested. Eventually elements with two layers were created on which the plant growth was monitored. The first tests were done in a greenhouse and an irrigation system was added. Eventually, tests were also done in an outside environment in Lyon. Irrigation remained included in the tests.

The results of this investigation included two patented mix designs. The mix designs consisted of cement, coarse aggregates (6 - 10 mm), water, superplasticizer and a viscosity modifying agent. In one mix design cement was partially replaced by metakaolin and limestone to reduce the pH. However, the chemical analysis showed that the pH of the pure cement mix design also decreased quickly to a value of 8.3 due to natural carbonation. This result suggested that obtaining a pervious concrete mix with a reduced pH value compared to normal concrete can be obtained without extra additives in the mix design. The study also showed that fertilizer addition was not necessary for the survival of the vegetation. However, it is possible that this conclusion changes when the length of the study is extended for several years. The water consumption of the pervious panels was on average 1 L/m^2/day. For germination and spring generation more water was needed.

2.2.3. Panels designed by Hemalatha et al. (2021)

The research by Hemalatha, Ranjit Raj, et al. (2021) focused mainly on the soil in which the plant grow. The experiments were done on a single layer pervious concrete element. The specimens were watered twice a day. The pervious mix design consisted of cement, coarse aggregate and water. Some mix designs contained fly ash as partial replacement of cement. The replacement had multiple reasons, firstly it improved the sustainability and secondly it was believed that the element oxides present in fly ash could act as micro-nutrients for the vegetation.

The comparison between the reference mixture without fly ash and the mixture with fly ash was not included in the research paper, so no prove of this believe was presented. It was observed that the aggregates of the mix design with a 30% void content withered off disturbing the shape of the elements. This phenomenon was not apparent in the mix designs with a higher binder content and thus a lower void ratio of 20%.

2.2.4. Conclusion

In Figure 2.2 pictures of the panels tested in the previously mentioned researches are included and Table 2.2 summarizes the test set-ups. The lessons learned from the previously mentioned research projects, can stimulate the development of the pervious concrete vegetated quay wall.

i. The pervious concrete panels as presented in the previous researches should be adapted to fulfil the demand for a self-sustaining quay wall

All the researches focused on a vegetated concrete element which is irrigated regularly, so the challenge is to find a system that is self-sustaining. No recommendations are given on this subject in these research papers, so other literature on improving the water retention properties of the pervious concrete should be used to improve this property.

ii. An appropriate pH-value can be obtained in pervious concrete mix designs without the use of extra additives

The plants do not directly live in the highly alkaline concrete, but live in the soil added to the pores of the pervious concrete. However, due to the contact between the concrete and the soil, the pH of the soil increases (Ottelé et al., 2011). Riley et al. (2019) experimented with the addition of metakaolin to reduce the pH value of the concrete, but proved that this addition is not needed for successful plant establishment. The other two research papers did not alter the mix design to reduce the pH-value of the concrete and both showed that vegetation without alterations is possible. It is important to note that this observation is only valid for vegetation that survives in an alkaline environment. Species that are successfully tested in one of the previously mentioned projects are Cymbalaria muralis, Asplenium trichomanes, Sedum, Thymus, Portuluca grandiflora and Trigonella foenum-graecum. When other vegetation is desired alteration of the mix design might be needed.

Since previous researches have indicated that the adaption of the pH-value is not crucial for vegetated pervious concrete, when appropriate species are chosen, the experiments in this thesis will not focus on this property and it will thus not be included in part II. For completeness of the literature review, methods for reduction of the pH-value of pervious concrete mixtures are included in the first part in paragraph 4.3.2.

iii. The interface between the pervious concrete layer and the structural layer is not a zone of weakness

Ottelé et al. (2011) and Riley et al. (2019) both use two layered panels for testing. Riley et al. (2019) performed a splitting test that showed that the adhesion between the two layers is sufficient, so the layers act monolythically. The interface zone is not specifically mentioned by Ottelé et al. (2011), but to the author's knowledge no problems did occur during testing of the green concrete panels.

Due to these experiments, the adhesion of the pervious layer to the structural layer is not considered in this research. The main focus will thus solely be on the pervious layer.

iv. Vegetated pervious concrete appears suitable in the application as quay wall covering, but some important properties are not yet determined to be able to state the potential of this application

The application as quay wall is not mentioned in any of the previously mentioned papers, but the assumption is that the pervious concrete mix designs that are proposed would also be suitable in this application. The compressive strength of the mix design proposed by Riley et al. (2019) and Hemalatha, Ranjit Raj, et al. (2021) is tested and appears to be appropriate for non-load-bearing applications. The aggregates of the mix design with a low cement content (81.3 kg/m^3) and thus a high void ratio of 30%

Table 2.2: Overview of the test set-ups of the vegetated pervious concrete projects by Ottelé et al. (2011), by Riley et al. (2019) and by Hemalatha, Ranjit Raj, et al. (2021)

	Ottelé et al. (2011)	Riley et al. (2019)	Hemalatha, Ranjit Raj, et al. (2021)
Aggregate	Lava stone of 32 millimeters	Aggregate of 6-10 millimeters	Coarse aggregate of 20 millimeters
Cement	Blast furnace slag cement	Cement with metakaolin and limestone filler	Portland cement with 0%, 25% and 50% fly ash
Porosity	Unknown	32%	25% & 30%
Test panels	Two layered	Two layered	Single layered
Soil addition	Soil mixture	Earth/compost with cement	Compost and garden soil
Planting method	Implanting cultivated plants	Seed sowing	Stem cutting and seed sowing
Testing location	Outside in botanical garden in Delft	Greenhouse and outside in Lyon	Unknown
Artificial watering	Irrigated	Irrigated	Irrigated

withered off and resulted in a change of shape of the specimens. This could also be a problem for the application as a quay wall, since disturbances at the surface can occur. For the mix designs with a higher cement content (162.6 kg/m^3) those problems did not occur. The freeze-thaw durability, the effect of de-icing salts on the vegetation and the underwater use of pervious concrete are also important to determine if the pervious concrete is suitable for quay wall applications. These properties are not included in any op the papers, so further research is needed to determine the potential.

When adjusting the mix design for the pervious concrete layer in the experimental phase of this study, the cement content should be kept high enough to prevent aggregates from withering off. The void ratio should not be too high. Furthermore, the freeze-thaw durability of the pervious concrete layer in combination with de-icing salts is checked in the experimental phase to better predict the suitability of this material in the application of a quay wall.

3
Framework

In this chapter the framework of the design is made by determining the ecological and technical requirements through literature research. Ecological requirements are set for the moisture needs, alkalinity, nutrient availability, surface roughness and root ability of the material. The technical specifications are restricted to a minimum compressive strength of the pervious layer and the durability of the product design.

3.1. Ecological requirements

The objective states that the current ecosystems on Dutch quay walls should be analysed, to conclude which properties are essential for the fulfilment of the ecological function. This corresponds to subquestion 1:

"Which type of vascular plant species are specific for the ecosystem on a traditional masonry quay wall and what (wall) characteristics allow the growth of those ecologically valued species?"

To analyze the ecosystem of quay walls of canals in Dutch cities several papers and articles have been assessed. Valuable quay wall plant species are selected, which determine the ecological requirements of the design. The goal is thus to find a representative ecosystem that can accommodate the majority of species.

3.1.1. Selection of plant species

A list of plant species is formulated to clearly describe the representative ecosystem. A specie is selected when it fulfils the following requirements:

1. To prevent endangerment the protection of this specie on walls is important, because the specie specifically occurs in wall environments (not or less in other habitats).
2. The specie was present on quay walls in freshwater canals in multiple cities in the Netherlands over the past twenty years. In other words, the conditions on Dutch quay walls are suitable for this specific type of plant.

First requirement: wall environment

The first requirement states that the habitat of the specie should primarily be on walls. To evaluate this the 1432 vascular plant species that regularly reproduce in The Netherlands are filtered on biotope. The organization FLORON divided the 1432 species in 37 ecological groups based on Arnolds (1979). The biotope "walls" consists of fifteen species, which are given in Table 3.1. Some species that are frequently encountered on quay walls in Dutch cities are not included, for example ferngrass. The reason that they are not included is that those species usually do not reach their optimum on walls. The loss of this environment would therefore have less impact on the extinction of these species. Although the focus is thus not specifically on those species, the establishment is not unpleasant, since the slower growth on walls make it able to coexist with the selected species (Maes and Krüse, 2011).

Furthermore, the species are divided in Red List categories. The levels of distinction are indicated in Figure 3.1. All species are red listed except for the species that are categorized as “Not Threatened at Present”. Half of the species in Table 3.1 are not threatened at present and are thus not on the Red List. Yellow corydalis, Spreading pellitory, Maidenhair spleenwort, Hart’s tongue fern and Black spleenwort were protected species in the Flora and Fauna Law. Due to an increase in numbers in the last decades as a consequence of awareness concerning wall plants, they are removed from the list of protected species. If the ecosystems in which those species occur are demolished, for example due to replacement of old quay walls, their numbers will decrease and they might become a protected specie again. It is therefore important to preserve the ecosystem when replacement is needed by designing bio-receptive quay walls.

Table 3.1: Selected species based on the first requirement (”wall” biotope)

Scientific name	Common name	Eco	Rarity class*	Red List 2012
Arabis hirsuta subsp. sagittata	-	6a	zzz	Susceptible
Asplenium adiantum-nigrum	Black spleenwort	6a	zz	Not Threatened
Asplenium ceterach	Rustyback	6a	zzz	Susceptible
Asplenium ruta-muraria	Wall-rue	6a	a	Not Threatened
Asplenium scolopendrium	Hart’s tongue fern	6a	a	Not Threatened
Asplenium trichomanes	Maidenhair spleenwort	6a	z	Not Threatened
Cymbalaria muralis	Ivy-leaved toadflax	6a	a	Not Threatened
Cyrtomium falcatum	House holly-fern	6a	zz	Not Threatened
Cystopteris fragilis	Brittle bladder-fern	6a	zz	Endangered
Erysimum cheiri	Wallflower	6a	zzz	Critically Endangered
Hieracium amplexicaule	Sticky hawkweed	6a	zzz	Susceptible
Parietaria judaica	Spreading pellitory	6a	z	Not Threatened
Pseudofumaria lutea	Yellow corydalis	6a	z	Not Threatened
Rumex scutatus	French sorrel	6a	zzz	Susceptible
Sedum cepaea	-	6a	x	Extinct

* a = general; z = quite rare; zz = rare; zzz = extremely rare; x = absent

Figure 3.1: Red List 2012 Categories. Left to right the level of endangerement increases.

Second requirement: ecological history of Dutch quay walls

The list of selected species is reduced by the second requirement using literature. Several articles on the ecosystem of quay walls in cities in the Netherlands published in the past twenty years are analyzed. The articles that are found include information about the vegetation on walls in city canals in Delft, Haarlem, Amsterdam, Woerden, Rotterdam, Utrecht, Amersfoort and Zeeland.

The article of Nonhof and van der Ham (2011) is about the wall vegetation in Delft. It focuses on the types of flora on the canal walls and bridges in the city centre and includes the numbers of ferns, which are counted in 2011. Furthermore, van Wieringen (2017 reported on the quay wall vegetation in and around the city centre of Haarlem and included a quantitative assessment. The assessment of the wall vegetation on quay walls in Amsterdam is documented in the paper by ten Hoopen et al. (2014), which contains quantitative information about the type and the location of species in the city. A quantitative overview is also provided of the quay wall plants in Woerden in the report by van Damme-Jongsten et al. (2011). Another journal article by Krüse et al. (2016) is shortly describing the measures for protection of wall vegetation in Utrecht, Rotterdam and Den Haag. Additionally,Andeweg (2007) published a report on behalf of Havenbedrijf Rotterdam N.V. to explore the flora of the Rotterdam port area. By indicating the type of vegetation, management and maintenance can be organised in a way that is beneficial for wall vegetation. The quay walls in Amersfoort have received much attention over the past years and an inventory of the plant species on the quay walls in the district Vathorst is done by de Wilde and Roskam (2015). Finally, the inventory report by Maes and van den Dool (2006) focuses on quay wall vegetation in Middelburg.

For the previously mentioned articles it is recorded, which plant species occurred on the invested quay walls. When a specie is encountered in an article, the specie got one point. In total the quay wall plant species in eight cities are evaluated, thus the highest possible score that a specie can obtain is a score of 8 points. When the specie is mentioned in at least half of the articles, so at least 4 times, it is regarded as a specie that fulfils the second requirement. The results of this literature review can be seen in Table 3.2, which is ordered by the number of cities the specie occurred in. The first eight rows are the final selected species that are used to determine the ecological requirements. This are five type of fern species namely maidenhair spleenwort, wall-rue, hart's tongue fern, black spleenwort and rustyback. Ivy-leaved toadflax, yellow corydalis and spreading pellitory are vascular plants which are also included in the selection. Pictures of the selected species can be found in Figure 3.2.

Table 3.2: Occurrence of plant species categorized by a ”wall” biotope on quay walls in Dutch cities

Scientific name	Common name	D*	H*	Ad*	W*	R*	U*	Af*	M*	Total
Asplenium trichomanes	Maidenhair spleenwort	1	1	1	1	1	1	1	1	8
Cymbalaria muralis	Ivy-leaved toadflax	1	1	-	1	1	1	1	1	7
Asplenium ruta-muraria	Wall-rue	1	1	-	1	1	1	1	1	7
Asplenium scolopendrium	Hart's tongue fern	1	1	1	1	1	-	1	1	7
Asplenium adiantum-nigrum	Black spleenwort	-	1	1	-	1	-	1	1	5
Pseudofumaria lutea	Yellow corydalis	1	1	1	-	-	1	-	-	4
Parietaria judaica	Spreading pellitory	-	1	1	-	1	-	-	1	4
Asplenium ceterach	Rustyback	1	-	1	-	1	-	1	-	4
Cystopteris fragilis	Brittle bladder-fern	-	1	1	-	-	-	-	1	3
Cyrtomium falcatum	House holly-fern	-	1	-	-	-	-	1	1	3
Erysimum cheiri	Wallflower	-	-	1	-	-	-	-	-	1
Sedum cepaea	-	-	-	-	-	-	-	-	-	0
Arabis hirsuta subsp. sagittata	-	-	-	-	-	-	-	-	-	0
Rumex scutatus	French sorrel	-	-	-	-	-	-	-	-	0
Hieracium amplexicaule	Sticky hawkweed	-	-	-	-	-	-	-	-	0

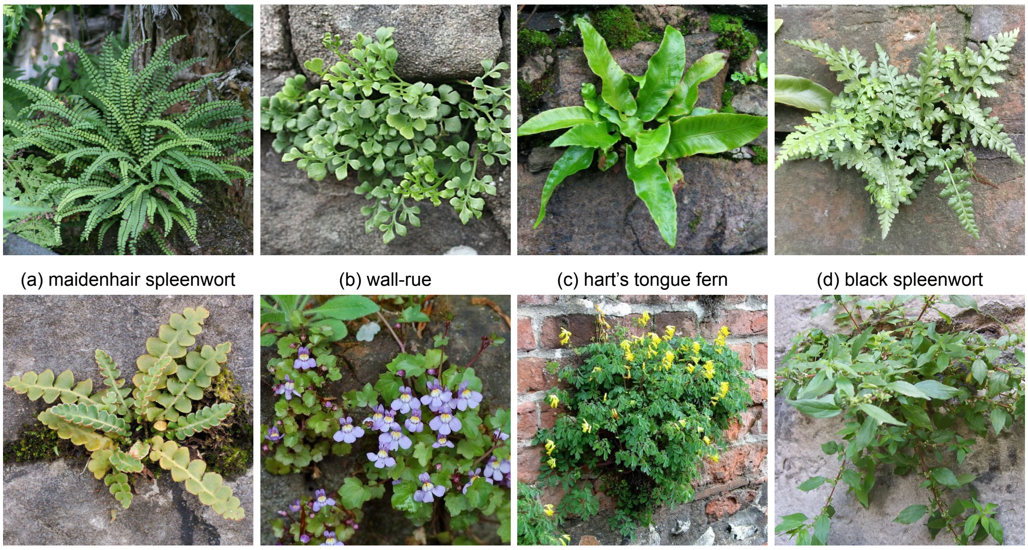
* D = Delft; H = Haarlem; Ad = Amsterdam; W = Woerden; R = Rotterdam; U = Utrecht; Af = Amersfoort; M = Middelburg

This selection is based only on qualitative data, namely if the specie is encountered on quay walls in certain Dutch cities in the last twenty years. Data on the number of individuals that is counted during inventory researches is only included in the articles and reports about Delft, Haarlem, Amsterdam and Woerden. Quantitative information of the final selected species is analysed to distinguish if a specie is ”very common”, ”common” or ”uncommon”. The rarity of the species can indicate how difficult it is to create the conditions for successful establishment of the species.

The pie charts in Figure 3.3 visualise the quantitative data. From this figure it becomes clear that *Asplenium ruta-muraria* is the most common specie, with large partitions in Delft, Haarlem and Woerden. In the pie chart of Amsterdam this specie does not return, because the specie is not counted there. However, a huge partition of *Asplenium ruta-muraria* is expected in Amsterdam since it is a common specie. Another specie that is left out of the research in Amsterdam is *Cymbalaria muralis*. This specie is also not included in the data of Haarlem, since only fern species are included there. In Delft and Woerden this specie is the second biggest, so the prediction is that the *Cymbalaria muralis* is frequently seen in Haarlem and Amsterdam. Furthermore, *Asplenium trichomanus* and *Asplenium scolopendrium* have a notable share in all four cities, with a remarkable number of *Asplenium trichomanus* in Amsterdam. All three species are categorised as ”very common”.

The species *Pseudofumaria lutea* and *Asplenium adiantum-nigrum* have a share in two of the four pie charts and are therefore categorised as ”common”. The number of individuals of *Pseudofumaria lutea* in Amsterdam and Delft is notable. This specie is not a fern specie and is thus not included in the research in Haarlem. *Asplenium adiantum-nigrum* is only part of the pie chart of Amsterdam and Haarlem.

In Amsterdam individuals of the uncommon species *Asplenium ceterach* and *Parietaria judaica* are found. The number of the first mentioned specie is quite high, but except for one isolated individual in Delft the specie is not occuring in any of the other data. *Parietaria judaica* is the least occurring specie in Amsterdam and is further not counted in the researches on the of the other three cities.



(a) maidenhair spleenwort (b) wall-rue (c) hart's tongue fern (d) black spleenwort

(e) rustyback (f) ivy-leaved toadflax (g) yellow corydalis (h) spreading pellitory

Figure 3.2: Pictures of the eight selected ecologically valued species

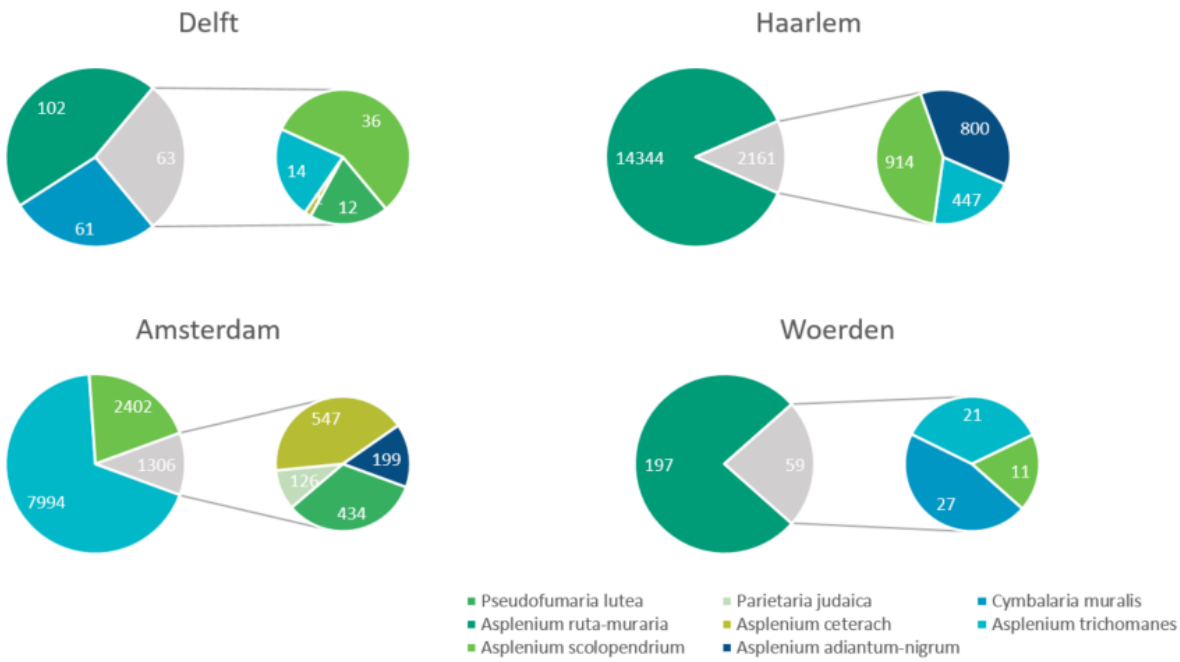


Figure 3.3: The number of individuals of the ecologically valued species counted during inventory researches over the past 20 years. In Haarlem only data on the fern species is included. In Amsterdam the commonly occurring *Asplenium ruta-muraria* and *Cymbalaria muralis* are not counted during inventory research.(Nonhof and van der Ham, 2011) (van Wieringen, 2017) (ten Hoopen et al., 2014) (van Damme-Jongsten et al., 2011)

3.1.2. Ecological requirements of plant species

The living conditions, for the eight species selected in the previous paragraph, will be at the base of the ecological requirements of the quay wall. History of vegetated traditional quay walls, helps to form the boundaries for the ecological requirements. The most vegetation is usually found on traditionally build masonry quay walls with lime mortar that are build more than twenty five years ago (Maes and Krüse, 2011). The wall characteristics that are responsible for this behaviour are analysed to underpin the ecological requirements obtained from the selected species.

In general, the following factors are indicated which influence the establishment and development of wall plants (Maes and Krüse, 2011):

1. Moisture
2. Alkalinity of root environment
3. Nutrients
4. Surface roughness and root ability

In reality these factors are interrelated, but for simplicity of this research the factors are evaluated separately to set ranges for the ecological requirements of the quay wall. Other factors such as temperature, light and availability of seeds and spores also influence the process. These factors are mostly influenced by the location and orientation of the quay wall and are indirectly taken into account in the selection of the preferred plant species. It is proven that these species can occur in a Dutch city quay wall climate. Local effects are not included in that analysis. If a vegetated quay wall is designed for a predetermined location with a specific orientation, this information can be taken into account in the selection of the preferred species. Apart from alterations of the design of the quay wall, some extra measurements could be taken to influence the location specific factors. The factor light can for example be influenced by the addition of a bumper beam or the addition of trees on the quay side, which can create shadow on the wall. These measurements can be considered separately from the main design. In this paragraph no further elaboration is thus given on the location specific factors, since the design of the quay wall can only minimally control them.

Moisture

i. Lessons from historical vegetated quay walls

From the traditional masonry quay wall construction it is known that a moisture containing environment is provided by the groundwater in the soil. The groundwater can reach the vegetation due to the porosity of the bricks and the joints after degradation. Since a modern quay wall is constructed with a water retaining element, usually a steel sheet piling, there is no direct contact between the finishing layer and groundwater in soil. Besides that, traditional thick masonry quay walls could store more water in the porous bricks, since the masonry consisted of multiple layers (Figure 1.1a) The half-brick bond, which is nowadays used only for aesthetic reasons, is too thin to store enough water (Figure 1.1b). This makes the water supply depended on rainwater that comes on and flows over the quay walls. This inconsistent supply results in big differences of moisture level, which is undesirable. In the design, techniques should be included that provide a constant moisture supply to the quay wall.

The richest vegetation develops on moist quay walls which lie in the shadow (Maas and Honingh, 2009. In the report by Andeweg (2007) it is stated that the damper the quay wall, the better the changes for establishment of plants are. However, there is also an upper limit to the maximum moisture content plants can survive. The roots will namely rot in a constantly wet soil. As a consequence of evaporation and the vertical position it is not likely that this upper limit will be reached in a quay wall.

Another aspect that influences the suitability of a wall is the positioning of the quay wall. When a quay wall is reclining, it namely provides better possibilities for water and nutrient accumulation, which positively stimulates plant growth. A small angle of inclination is often possible for a quay wall, but is kept out of consideration at this stage of the research, since it is project depended if inclination of the qua wall is allowed.

ii. Wall characteristics based on selected plant species

The Ellenberg indicator value for moisture (F) is used as an indication of the preferred moisture level per specie. The value F is on a scale from 1 to 9, where 1 corresponds to an extremely dry soil and 9 corresponds to a wet soil. The intermediate steps are arranged according to Figure 3.4. In table 3.3 the values per specie are specified and Figure 3.4 visualises the preferred moisture level per specie. The species are evenly distributed on a wide range from a dry soil to a damp soil. To better specify this range the ecological requirement is set to be the intermediate indicator, namely a moist soil. The moist soil indicator is specified as ”mainly on fresh soils of average dampness, absent from both wet and dry ground”.

From experience it is concluded that the problem in walls is rarely a too wet substrate. More often vegetation is restricted due to the dryness of the wall. The goal is thus to produce a quay wall that is always moist. In practice the plants can survive a certain dry period as long as the root system survives the drought. The length of this dry period is taken as the lower boundary condition for the moisture level.

Determining an exact number for the time a certain plant specie can survive without water is difficult, since this depends on multiple factors such as the root structure, the substrate it is in, the humidity of the surroundings, the time of the year and the amount of sunlight. It is thus difficult to put an exact number for this lower boundary. An estimation is made based on experiences in the past and expectations for the future. History showed that quay wall plants often revive after a dry summer. In this time the evapotranspiration is high and the precipitation is low, which can last for some months. Due to climate change, the Netherlands will face more extreme drought periods, due to limited precipitation and increased temperatures and sunlight radiation. Therefore the limit is set at a maximum dry period of 2 weeks.

An equally distributed moisture level will probably not be achieved. Instead a moisture gradient will be seen on the wall. The local circumstances will control the germination of different species on different heights.

Alkalinity

i. Lessons from historical vegetated quay walls

Traditionally lime mortar is used for masonry quay walls, but in the previous century this type of mortar is usually replaced by modern Portland cement. A big difference between the two types of mortar is the pH-value: Portland cement has an initial pH-value of 11-12 and lime mortar an initial pH-value of 8-9. The quay walls with lime mortar show more vegetation and are more beneficial for the establishment of organisms, which insinuates a relation between the pH-value and the vegetation (Maes and Krüse, 2011).

Over time the pH-value of both types of mortars reduces due to carbonation and bacterial growth. Since more vegetation is seen on older walls, a reduced pH-value is related to better opportunities for the establishment of vegetation. However, weathering does not only effect the pH-value of the wall, but also influences other wall characteristics, such as porosity of bricks and joints, which makes direct relation debatable.

Both the mortar type and the age of the quay wall suggest that a weakly alkaline environment (pH < 9) is best for wall vegetation. Experiments done by Lubelli et al. (2021) show that pioneer plant species, like ivy-loaded toadflax and yellow corydalis, can already grow in mortars three months after preparation. Mortars with lime-trass perform the best with regard to germination of seeds. Mortars with natural hydraulic binder and blast furnace slag cement (low pH cements, so initial pH < 11) show positive results as well, but no seedlings are observed in joints with Portland cement mortar. This demonstrates that the initial pH-value of mortars, except for the Portland cement mortar, is suitable for germination of seeds. A pH-value that is somewhat above the previously mentioned limit of 9 is apparently also suitable.

ii. Wall characteristics based on selected plant species

Taking into account the preferred plant species on the wall, the range for the pH-value of the root environment is determined. Most wall plants prefer a neutral to alkaline environment. To better demarcate the pH-range, the Ellenberg values for vascular plants are used. Ellenberg values are indicator values that describe the ecological behaviour of plants. One of the environmental factors that is described is the soil alkalinity, which is described by the factor reaction figure (R). This is a number on a scale from 1 to 9, which qualitatively indicates the level of alkalinity. The qualitative description of the levels is indicated in Figure 3.4 and the values per specie are specified in Table 3.3.

Table 3.3: Ellenberg values for moisture figure (F), reaction figure (R) and nitrogen figure (N) for selected plant species

	Moisture F	Alkalinity R	pH (H_2O)	Nitrogen N
Asplenium adiantum-nigrum	4	2	4,0	3
Asplenium ceterach	3	8	8,5	2
Asplenium ruta-muraria	3	8	8,5	2
Asplenium scolopendrium	5	8	8,5	4
Asplenium trichomanes	5	X^*	-	3
Cymbalaria muralis	6	8	8,5	5
Parietaria judaica	7	8	8,5	7
Pseudofumaria lutea	6	9	10,5	5

$^*X$ is used for indifferent or very varied behaviour

In Figure 3.4 the preferred alkalinity level for the plant species is visualised. Most plant species prefer a neutral to basic environment. Only one plant specie prefers an acid environment. This is an unexpected observation, since specie selection is based on the fact that the species occur on quay walls, which almost always provide a neutral to basic environment. This specie is disregard when determining the pH-range. The pH-value thus has to be around R is 8, since almost all species have a R-value of 8, which corresponds to a neutral/basic environment.

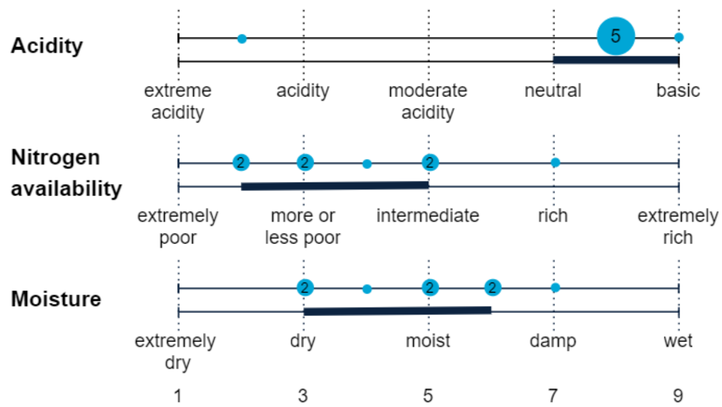


Figure 3.4: Visualisation of the Ellenberg values on a scale from 1 to 9 with a qualitative explanation of the different levels per indicator value

To give meaning to the Ellenberg values, a calibration of the indicator values is carried out on a large database with environmental variables in the Netherlands (Ertsen et al., 1998). A satisfying relationship between the Ellenberg value for alkalinity and the soil pH is found. The optimal soil pH-value for each selected plant specie is calculated by the relationship given in Equation 3.1. The results are included in Table 3.3.

$$pH(H_2O) = 0.42 + \frac{39.38}{12.90 - mR} \tag{3.1}$$

Since the plants are living on a wall, the soil pH-value might not perfectly correspond with the pH of the wall. The pH-values obtained with the calibration equation should therefore be compared to values found in literature to review if the values are an accepted approximation for the pH of the wall. However, insufficient reliable sources are found that provide information on the optimal pH-value of a wall for the selected species. The optimum pH-range for *Asplenium scolopendrium* is specified by de Wilde and Roskam (2015) and is specified as 7.5 to 8.6. The optimal pH-value calculated from the Ellenberg indicator value R for this specie is 8.5. It would suggest that the calculated values are justifiable, but at the high side of the range. However, one comparison is not enough to make a fair judgement. The pH-values calculated with Equation 3.1 are thus an approximation and using them as a hard condition requires extra validation.

As mentioned before, the desired alkalinity of the wall is around R is 8, which corresponds to a pH-value of 8.5 according to Equation 3.1. Taking into account the fact that extra validation is needed to set hard requirements and that experience with mortar type and age of quay walls showed that a weakly alkaline environment (pH < 9) is suitable for the growth of specific wall species, a pH-range of 8 to 9 is set as a ecological requirement.

Nutrients

i. Lessons from historical vegetated quay walls

Plants that are characteristic for wall environments are known for their capability to survive in extreme environments, with low availability of nutrients. The creation of a suitable environment for wall plants is a time consuming process. The formation of fissures and cracks in the walls triggers the accumulation of dust and living organisms such as bacteria, lichen and fungi, provide dead organic matter. This induces the formation of soil, which provides nutrients for pioneer plant species. Weathering is not only important for the formation of cracks, but calcium is released as well, which influences the pH-value and is also an important nutritional element for plants. Therefore calcium rich walls are ideal for most wall species. After the establishment of pioneer species, nutrient levels are maintained at an appropriate level due to dead organic matter of roots of plants. A circular ecosystem thus exist.

To make a initial bio-receptive quay wall, the long-term process should be skipped. An appropriate environment should be created from the start. This is done by adding a mixture to the pervious layer after curing, that resembles the properties of the naturally formed mixture. Washout of nutrients might be a problem if germination of the first plants takes too long. At the other side of the balance an excessive amount of nutrients, caused by addition of extra nutrients, may cause weeds to overgrow, which suppresses the selected species. The difficulties lie thus primarily in the beginning phase, before the circular ecosystem has been established.

ii. Wall characteristics based on selected plant species

The nutrient absorption of plants is strongly related to the pH-level of the soil. Since the correlation is not taken into account in this research, an appropriate nutrient level should be determined independently from the alkalinity level. The Ellenberg indicator value for nitrogen availability (N) can be used as an indication of the nutrient level that is preferred per specie. The value N is on a scale from 1 to 9, which corresponds to a scale from extremely poor to extremely rich nitrogen availability. In table 3.3 the values per specie are specified and in Figure 3.4 the preferred nitrogen level per specie is visualised. Most of the selected plant species prefer a poor to intermediate nitrogen availability. Only one specie prefers a rich nitrogen environment. Since this is the case for only one out of eight and it does not match the general description of the nutrient needs of wall plants, the ecological requirements of the design are not influenced by this outlier.

Surface roughness and root ability

i. Lessons from historical vegetated quay walls

As described before, quay walls with lime mortar show more vegetation. Apart from the lower pH-value of lime mortar, lime mortar is more suitable due to its rough surface. Calcareous lime mortar joints become rougher and more porous over time than joints made of Portland cement, since Portland cement has a higher hardness. This process occurs due to chemical reactions and organisms such as bacteria, lichen, algae and fungi.

Organisms such as bacteria, lichen, algae and fungi make the surface of bricks and mortar rougher. On a rough surface dust, seeds and other organic material can accumulate, which is important for the formation of an appropriate root environment and the dispersal of seeds and spores. A rough surface also offers grip and space to root (Maas and Honingh, 2009).

ii. Wall characteristics based on selected plant species

Surface roughness and root ability are not specified by the Ellenberg indicator factors. They are less specie specific than the other factors and are therefore described in general for vascular plant species.

Root ability is related to open porosity. Open porosity describes the amount of interconnected pores in a material. The interconnected pores provide space for roots, but also allow for accumulation of water and nutrients. This function requires an even higher open porosity ratio, than the ratio that is required for the space the roots require. Tamai et al. (2004) suggested a minimum interconnected void ratio of 18% for viable growth and a minimum ratio of 25% for immediate growth. Quan (2012) assumed a void ratio of 30% is needed for viability of vegetation. A minimum ratio of 18% is used as an ecological requirement. A higher value is most likely beneficial for the vegetation, but the value is restricted by the technical requirements. Higher porosity namely results in lower compressive strength.

The research by do Carmo et al. (2016) used linear regression to determine the relation between surface roughness and plant richness, abundance and total plant cover. They show a strong positive correlation. The research included vertical irregularities up till 30 centimeters. A higher surface roughness thus improves the opportunities for plants at least till the limit of 30 centimeters. The surface roughness will be limited by the technical requirements, since increased porosity and therefore increased surface roughness, reduces the compressive strength. The goal is thus to maximize the surface roughness whilst fulfilling the technical requirements.

3.1.3. Conclusion

An overview of the ecological requirements that are set for the substrate layer of the quay wall are given in Table 3.4

Table 3.4: Ecological requirements of the pervious layer defined for the framework of the design

Requirement	Boundaries	Comments
Moisture	Dry period < 2 weeks	Upper boundary is less important.
Alkalinity	pH-value in between 8 and 9	-
Nutrients	Poor nitrogen availability	Especially important at the beginning.
Porosity	>18%	Limited by the technical restrictions
Surface roughness	As high as possible	Limited by the technical restrictions

3.2. Technical requirements

The structural layer and the connection between the structural layer and pervious layer are not considered in this research as the structural layer is designed in accordance with the Dutch concrete standards (NEN) and the interaction between the structural layer and pervious layer never caused failure in past studies. The technical requirements are thus restricted to the pervious concrete finishing layer. For the finishing layer of the concrete quay wall element, no standards are found, so the requirements for the finishing layer are drafted from assumptions.

3.2.1. Compressive strength

The pervious concrete as a finishing layer is a non-load-bearing application. However, minimum strength is needed for self-support and support of the soil, the vegetation and the water retained by the concrete and the soil mixture. Many mechanical characteristics of concrete show a certain coherence with the compressive strength. This is reflected in the Eurocode when considering the design values for compressive strength, tensile strength and elastic modulus, which are all associated to the strength class. For this reason, only the compressive strength of the pervious concrete is considered for determining the strength of the finishing layer.

To obtain a minimum value for the compressive strength of the pervious concrete, the minimum strength of the finishing layer should be considered. As mentioned before, no specific values are mentioned in the standards, so an alternative method is used to determine the minimum compressive strength. A compressive strength of approximately 6 MPa is required for non-load-bearing structural walls (Subramaniam et al., 2022). As a finishing layer is similar to a non-load-bearing wall, a minimum 28-day compressive strength of 6 MPa is used during this investigation.

3.2.2. Durability

The environment impacts the durability of the concrete and is defined by the environmental class. The concrete can be exposed to multiple environmental classes. Only two environmental classes are important for concrete without reinforcement: the freeze-thaw environment and exposure to chemical attack. Concrete can be exposed to chemical attacks when it is in contact with soil and groundwater containing high concentrations of chemical elements such as sulfur, ammonium and magnesium. The pervious concrete layer is not in contact with the soil layer, thus this environmental class is not applicable. There are four sub categories that define the freeze-thaw environment to which the concrete is exposed, which are classified by XF1, XF2, XF3, and XF4. These categories give information about the amount of water and the occurrence of deicing salts as specified in Table 3.5. The pervious concrete layer that is in the vertical position can be considered as class XF2. For the capping stone another environmental class should be considered (XF4).

Table 3.5: Freeze-thaw environmental classes

Environmental Class	Description	Example
XF1	Not completely saturated with water, without de-icing salts	Vertical concrete surfaces exposed to rain and frost
XF2	Not completely saturated with water, with de-icing salts	Vertical concrete surfaces exposed to rain and frost and to de-icing salts carried by air
XF3	Completely saturated with water, without de-icing salts	Horizontal concrete surfaces exposed to rain and frost
XF4	Completely saturated with water, with de-icing salts	Horizontal concrete surfaces exposed to rain and frost and to de-icing salts

En 206 dictates the maximum water-to-cement ratio for environmental class XF2 is 0.55 and the minimum strength class is C25/30 (Table F.1). It also sets a boundary for the minimum amount of cement paste per volume of concrete. However, due to the application as a non-structural finishing layer made of pervious concrete instead of conventional concrete, these values cannot be used as boundaries. Although the currently mentioned boundaries are thus not used and no boundary is set for the maximum damage by freeze-thaw cycles on forehand, this phenomenon is tested in part II and shall be taken into account when evaluating the mix designs.

The pervious concrete layer produced in Oudenbosch by Holcim Bouw&Infra is tested for its freeze-thaw durability. This layer consists of coarse lava stone aggregates in the fraction 16/32 mm. Additionally, a fine aggregates green wall layer made by LafargeHolcim is tested according to the same method. Coarse aggregates of the fraction 1.6/3 mm are used for this layer. The results are included in Figure 3.5. After 18 FT cycles the mass loss of the previously mentioned mix designs is approximately 40% and 10%, respectively. As the fraction used for the finishing layer of the quay wall is in

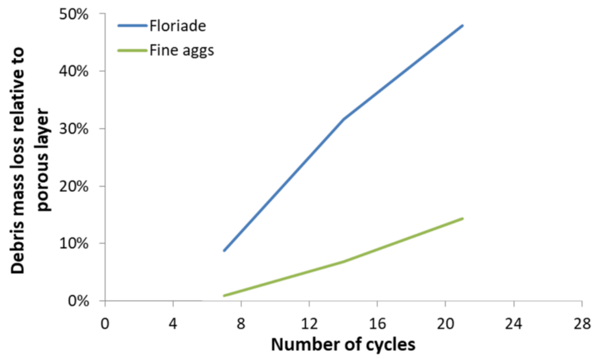


Figure 3.5: Cumulative mass loss during FT cycles for the pervious concrete layer produced by Holcim Bouw&Infra with 16/32 mm lava stone aggregates (Floriade) and for the fine aggregates green wall layer produced by LafargeHolcim with 1.6/3 mm aggregates (LafargeHolcim, 2021)

between the two tested fractions, the expected freeze-thaw damage is approximately 25% after 18 cycles. This expectation is used as a non-strict requirement to be able to compare the mix-designs. Slight exceeding of this requirement does not mean that the mix design is completely inappropriate.

3.2.3. Conclusion

An overview of the technical requirements is given in Table 3.6. Apart from the compressive strength boundary values for the materials and the production method are included. No boundary value for the freeze-thaw performance is included, since it is known that pervious concrete behaves poor in this situation. The goal will be to minimize the damage due to FT cycles, but since damage is expected in all types of pervious concrete, no maximum value is considered at this moment.

Table 3.6: Technical requirements of pervious layer defined for the framework of the design

Category	Requirement	Value
Materials	Aggregate size	> 8 mm
	D_{max} - D_{min}	< 8 mm
Production	Curing temperature	20 - 30 °C
	Curing humidity	80 - 95 %
Performance	Environmental class	XF2
	Mass loss after 18 FT cycles	< 25%
	Life time	50 years
	28-Day compressive strength	6 MPa

4
Material properties

In this chapter a literature review on the material properties of pervious concrete is included. The first paragraph discusses general information on pervious concrete. The second paragraph gives information on the constituents of pervious concrete and the effect of those constituents on the general properties. In the last two paragraphs, the material properties are related to the ecological and technical requirements.

4.1. Introduction to pervious concrete

Pervious concrete is a special type of concrete with little to no fine aggregates. A narrow gradation (homogeneous or gap-graded) of coarse aggregates in combination with a limited amount of cement paste, creates a concrete with high porosity. Due to the coverage of the surface of the aggregates with cement paste, bonds are formed at the contact points. The addition of cement paste is insufficient to fill the open pores, which results in an interconnected porous concrete, also known as pervious concrete. A sketch of the build-up of pervious concrete is shown in Figure 4.1. The voids between the cement coated aggregates are referred to as macro-pores. On a much smaller scale there are also pores in the cement paste which are referred to as micro-pores.

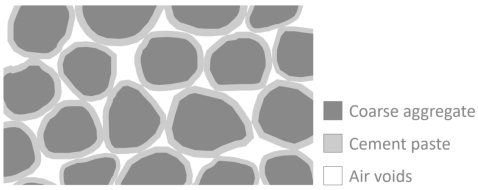


Figure 4.1: Sketch of the build-up of pervious concrete consisting of three components

The terms porous concrete and pervious concrete are often interchangeably used, but the definition is not exactly the same. The pore structure in porous concrete is not per definition interconnected, while pervious concrete always has connected macro-pores, which makes it water permeable (Tang et al., 2022). Due to the specific build-up of pervious concrete, a relative low density of 1600 to 1900 kg/m^3 can be obtained (Banevičienė et al., 2022). However, increased porosity reduces the strength properties, which limits the application of pervious concrete. The mechanical properties are mainly depended on the strength of the aggregates, the strength of the cementitious material and the cement coating thickness. Another disadvantage of pervious concrete is its poor resistance to FT cycles, because of the high water absorption due to the interconnected macro-pores. The average pore diameter of the macro-pores is greater than 1 mm, which means that the capillary effect in pervious concrete is insignificant (Tang et al., 2022). This is usually regarded as a benefit, but for the use as a vegetated quay wall it is considered a drawback as water transport from the canal to the quay wall is insignificant to provide moisture for the vegetation on the wall. The design of pervious concrete is clearly a trade-off between the mechanical strength properties, the durability, the connected porosity ratio and the water characteristics.

Seeni and Madasamy (2021) reviewed major factors that are involved in the design of pervious concrete mixes and provides ranges for the properties of pervious concrete based on literature research. Table 4.1 includes the findings of this review for the mixes with aggregates sizes near the range of 8 to 16 mm. In this paper it is acknowledged that the upper boundary for the compressive strength is usually significantly lower than the 79 MPa from the table, mentioning values of approximately 30 MPa (*522R-10: Report on Pervious Concrete*, 2010). The range for the compressive strength is higher than the requirement of 6 MPa, indicating that it is most likely possible to make a mix design that fulfils this condition. However, the WCR range is limited by the upper boundary of 0.4. increasing the WCR above 0.4, to improve the water retention capacity, reduces the compressive strength. Research is needed to determine the exact impact. The requirement has set the lower limit of the void ratio to be 18% which is within the range from Table 4.1.

Table 4.1: Properties of pervious concrete with a coarse aggregate fraction near the range of 8 to 16 mm according to Seeni and Madasamy (2021)

Property of pervious concrete	Range
Water-to-cement ratio (WCR) [-]	0.2 - 0.4
Aggregate-to-cement ratio (ACR) [-]	2.14 - 6.92
Cement content [kg/m^3]	242 - 532
Void ratio [%]	13 - 37
Compressive strength [Mpa]	8 - 79
Density [kg/m^3]	1620 - 2435

4.2. Concrete components

From Figure 4.1 it becomes clear that pervious concrete consists of three elements: coarse aggregate, cement paste (cement and water) and air voids. Besides those main elements, fillers and admixtures can be added to the mix design to enhance specific properties. In this paragraph general information about the constituents of pervious concrete is given.

4.2.1. Coarse aggregate

Aggregates form the skeleton of the pervious concrete and take up the biggest volume. Different aggregates can be distinguished based on geometrical and physical characteristics.

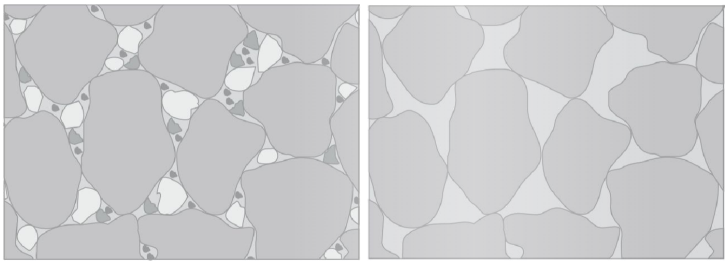
Particle size

Aggregates with various particle sizes can be used in the production of concrete. Fractions, with a lower (d) and an upper (D) particle size limit, are used to group the particles. A group of particles can thus be described by d/D . For example particles within the range of 8 to 16 mm are described as the fraction 8/16. The particle size distribution can be determined by performing a sieve analysis on the raw material.

Aggregates with a particle size bigger than 4 mm are referred to as coarse aggregates and are the main constituent of pervious concrete. Pervious concrete has a homogeneous particle size distribution, which increases the number of pores with regard to a heterogeneous particle size distribution (Figure 4.2). Apart from a homogeneous particle size distribution, the porosity is also increased when the particle size is increased. This means that the use of fraction 18/26 results in a higher porosity than the use of fraction 8/16 despite of the same homogeneous particle size distribution width. The porosity is related to many other properties which is explained in paragraph 4.2.4.

Particle shape and roughness

Besides the particle size, the particle shape and the roughness are important for the final concrete product. Rounded aggregates result in a better workability of the concrete mix compared to crushed



(a) Heterogeneous particle distribution (b) Homogeneous particle distribution

Figure 4.2: Types of particle size distribution and the influence on the build up of pervious concrete

angular aggregates and have a lower need for mixing water. Therefore the water-to-cement ratio can be reduced for round aggregates, which improves the strength properties of the binder, which is discussed in more detail in paragraph 4.2.3. Contrary, crushed aggregates usually have a rougher surface, which is beneficial for the bonding strength between the aggregates and the cement paste and thus improves the strength properties.

Density
The dry particle density relates the dry mass to the volume, which includes the particle material volume and the internal pore volume. The porosity of the material is thus influencing the particle density. When the inter-particle void volume is included, the bulk density of the material is obtained. This parameter is often used in industry, but is less suitable for small scale experiments.

Water absorption
Aggregates can absorb water, which influences the moisture content of the material and in turn affects the particle density. Highly porous aggregates, such as lightweight aggregates, can absorb a lot of water. Water absorbed by the aggregates is not available for the hydration of cement. When using dry aggregates, the addition of extra water to the mix design, based on the water absorption of the aggregate, is needed to ensure complete hydration of the cement.

Since aggregates are usually stored outside, the moisture content will vary during the production process of concrete. A constant ratio between the dry mass of the aggregates and other constituents should be used as the wet mass is depended on the moisture content. Therefore the dry mass of the raw materials is converted to the wet mass depended on the moisture content of the aggregates. The amount of mixing water is also adapted based on the moisture that is already added in the form of absorbed water.

Strength
The mechanical strength of the aggregates is usually greater than the intended compressive strength of the concrete. As a result the strength of the cement and the bonding strength between the aggregates and the cement are normative for the strength of the concrete. (ENCI, Mebin, & Sagrex, 2015) However, when lightweight aggregates are used, it is also possible that failure occurs due to breakage of the aggregate.

4.2.2. Cement

Cement is used as a hydraulic binder in concrete due to its chemical reaction with water, which is called hydration. During hydration, calcium silicate hydrate crystals and calcium hydroxide crystals are formed, which partially replace the pores that are initially filled with water. This results in setting and hardening of the cement paste (Saleh and Eskander, 2020).

Cement types
Cements conforming to the cement standard (EN 197-1) are termed CEM cement and are subdivided into the following categories:

- CEM I Portland cement

- CEM II Portland-composite cement
- CEM III Blast-furnace cement
- CEM IV Pozzolanic cement
- CEM V Slag-pozzolanic cement
- CEM VI Composite cement

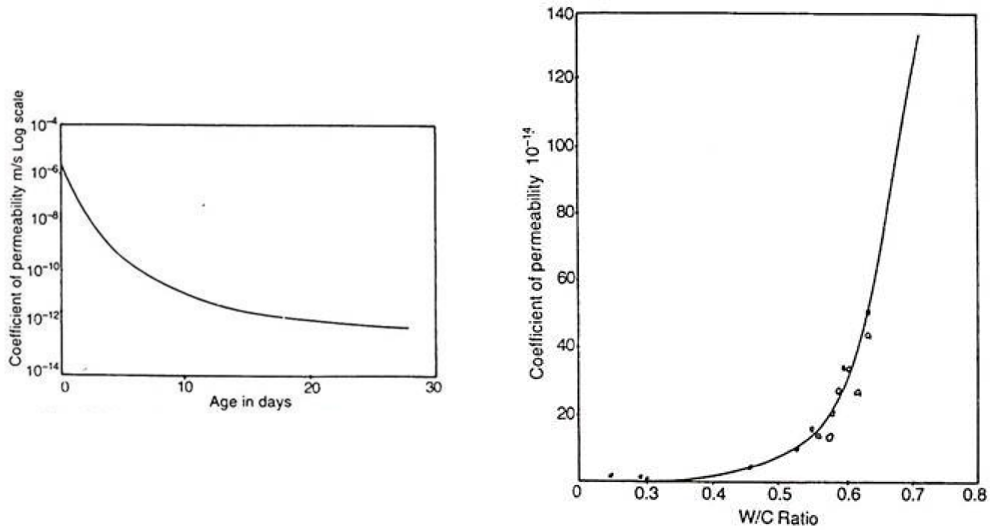
Portland cement clinker is at the base of these cement types, but the amount of clinker differs per category. The clinker content is indicated by the letters A (highest clinker content), B (intermediate clinker content) and C (lowest clinker content). Furthermore, alternative binders such as granulated blast furnace slag (S), pozzolanic materials (P, Q), fly ashes (V, W), burnt shale (T), limestone (L, LL) and silica fume (D) are added in different percentages per cement category to partially replace Portland clinker. In the notation of the cement type a capital letter is used to indicate the main constituent besides clinker. The cement notation also includes a number which represents the strength class: 32.5, 42.5 or 52.5. The last letter in the notation indicates the speed of the initial strength development: L (low), N (normal) or R (rapid). For example, blast furnace cement in strength class 42.5 and with normal strength development is notated as: CEM III/B-S 42,5 N. ("Cement", 2011)

Ordinary Portland cement (OPC) and blast furnace cement are the most commonly applied cement types in the Netherlands. In blast-furnace cement, the ground blast-furnace slag partially replaces ground Portland clinker. Blast-furnace slag is a by-product which is obtained from the production of iron and steel in the blast-furnace process. This waste product from the steel industry is reused in a useful way and therefore environmentally beneficial in comparison to OPC. However, CO_2 is emitted by the iron and steel industry, which is not taken into account when considering this material as a by-product. For the production of pervious vegetated concrete a suitable type of cement should be selected that best fits the ecological and technical requirements.

Pore structure of cement paste
The pore structure of the cement paste in closely related to mechanical and durability properties. The pore structure can be characterized by the porosity, pore size distribution, pore tortuosity and the pore connectivity. The pores in cement paste can be classified into five groups: gel pores (1-10 nm), capillary pores (0.01 - 0.1 μm), submicron large pores (0.1 - 1 μm), micron large pores (1 - 10 μm) and macro-pores (>10 μm). There are various methods for the characterization of the pore structure and a combination of experimental methods is needed for realistic determination of all pore parameters. Some methods use dried samples for testing. It should be noted that drying the samples prior to testing may damage the micro structure of the material irreversibly.

The internal pore structure of cement paste is closely related to the transport properties. Capillary pores (0.01 - 0.1 μm) have a high correlation with the initial absorption stage, the secondary absorption stage and the cumulative water absorption (He et al., 2022). Larger pores also influence water transport, but to a lesser degree than capillary pores. The capillary pore structure is primarily influenced by the WCR of the cement mixture. Water that is not used for the hydration namely causes the formation of the capillary pores. The relation between the WCR and the porosity is shown in Figure 4.3b and indicates that an increase in WCR is strongly increasing the permeability. An increased degree of hydration and thus age, decreases the volume and size of the pores (Ye, 2005). This results in reduced permeability after longer curing time as can be seen in Figure 4.3a.

Aggregate-to-cement ratio
A lower aggregate-to-cement ratio (ACR) increases the thickness of the cement paste coating along the surface of the aggregate, but only if the cement paste has appropriate rheological properties. If this is not the case, the cement paste accumulates at the bottom of the concrete instead of forming a thicker layer. A thick coating results in higher bond strength, but reduces the interconnected porosity, so the thickness of the cement layer should be carefully balanced (Torres et al., 2015). One well known parameter describing the rheological properties of the cement paste is the viscosity. Xie et al. (2018) studied the relation between the rheological properties of cement paste and the maximum paste coating



(a) Relation between permeability and the progress of hydration (Neville, 1981)

(b) Relation between permeability and WCR for mature cement pastes (Neville, 1981)

Figure 4.3: Relations between internal pore structure and the permeability of cement pastes

thickness (MPCT). The relationship showed that the maximum paste coating thickness is depended on the apparent viscosity, the surface texture of the aggregate and a coefficient indicating the sensitivity of the MPCT to the viscosity of the cement paste. Furthermore, it is found that an increased aggregate size reduces the coating thickness. Increased aggregate size namely reduces the contact area and increases in macro-porosity, which makes drainage of free paste a bigger problem. The addition of a small amount of fine aggregate makes it possible to increase the ACR ratio, without accumulation of the cement paste at the bottom due to the increased contact area of the aggregates.

In general a range for the aggregate-to-cement mass ratio (ACR) between 4 and 6 can be used for pervious concrete with appropriate porosity (Sonebi et al., 2016). This range leads to an aggregate content of 1200 to 1800 kg/m^3. However, the density of the coarse aggregate should be considered when using these ranges. For lightweight coarse aggregate material this ratio should be adapted according to the bulk density. For example a material with a bulk density of 500 kg/m^3, has an ACR of approximately 1.1 to 2.5.

4.2.3. Water

Hydration of cement cannot take place without water. The water demand of the mixture is related to the particle size distribution, particle shape and the desired consistency. Coarsely graded aggregates have a lower mixing water demand than fine graded aggregates. The water-to-cement mass ratio (WCR) is an important parameter for the mix design that influences both the strength and the durability of the concrete. The consistency of the cement paste is greatly depended on the WCR, but also on the addition of admixtures. One gram of ordinary Portland cement binds approximately 0.23 gram water and absorbs 0.19 g water, which results in a minimum WCR of 0.42 for complete hydration (Gruyaert, 2011). However, at higher WCRs, the porosity of the concrete increases which negatively effects the strength and durability of the concrete. The WCR should thus be carefully balanced to obtain concrete of good quality.

The National Ready Mixed Concrete Association (NRMCA) specified the following boundary for the WCR: 0.3 to 0.34. Other articles mention a wider range of 0.2 to 0.34 (Pedram et al., 2022) (Hoshitha et al., 2022) (Seeni and Madasamy, 2021). These low boundaries can be explained by the fact that coarse aggregates need less mixing water than mix designs including fine aggregates, due to the lower surface area of coarse aggregate. However, it is possible to make pervious concrete with higher WCRs with the addition of admixtures. The admixtures should increase the internal cohesion of the cement paste to avoid segregation of the cement paste and the coarse aggregate. An example of an admixture that increases internal cohesion is Cugla Colloidal 100, which is applicable in one grain concrete. Another solution is the addition of micro-cellulose fibers to obtain the desired cosistency.

4.2.4. Pores

Pervious concrete has three levels of porosity: (1) the macro-scale pores between the aggregate and the cement paste, (2) the micro-scale pores in the cement paste material and in the aggregate material and (3) the nano-scale pores contained in the cement hydration products. Macro scale pores in concrete can be closed or connected. Closed pores are not connected to each other or the outside environment and do not impact the effective porosity. Connected pores are interlinked and form a skeleton of pores inside the material. According to Liu et al. (2019) 10 to 20% of the pores in pervious pavement concrete are closed and the other pores are connected. The National Ready Mixed Concrete Association (NRMCA) of America specified the following boundary for pervious concrete: An open porosity between 15% and 25%. Other articles state a higher upper limit for porosity, namely a porosity reaching up to 37% (Pedram et al., 2022) (Hoshitha et al., 2022) (Seeni and Madasamy, 2021). As mentioned before, the continuous porosity is an fundamental property of pervious concrete. It influences many properties such as the compressive strength and the durability. The water permeability of pervious concrete is linked to the interconnected porosity.

Soltani (2022) found that the porosity is reduced by 30-40%, when the aggregate size is reduced from 8 mm to 2.83 mm, which shows the clear impact of this parameter on the porosity. This finding is confirmed by Yu et al. (2019a), which showed a positive correlation between the particle size of the coarse aggregate and the water permeability and thus the interconnected porosity. Furthermore, narrowing the gradation of the particle sizes and decreasing the cement paste volume have an increasing effect on the open porosity. Mixtures containing angular coarse aggregate tend to have a greater porosity than mixtures with rounded or semiangular aggregates, since less angular particles can be compacted better (Kevern et al., 2010). Compaction by vibration as used for conventional concrete, is not suitable for pervious concrete, since this causes cement paste accumulation at the bottom, which results in a lower void ratio at the bottom than at the top. On the other side, compaction by hand results in a heterogeneous mix with low mechanical strength. Impulsive compaction methods are therefore quite often used for compacting pervious concrete, since the compaction energy of this method is in between the previously mentioned compaction methods. (Seeni and Madasamy, 2021)

4.3. Material properties related to the ecological requirements

In this paragraph it is discussed how the five ecological requirements, which are determined in paragraph 3.1 can be obtained in pervious concrete.

4.3.1. Moisture

The optimization of the water retention capacity of pervious concrete is the main challenge as vegetated pervious concrete is usually not applied in a application without irrigation. By increasing the water retention capacity of the substrate layer, more water is available for the vegetation on the quay wall over time. It should be noted that increasing the water retention capacity of the pervious concrete results in a lower freeze-thaw durability, particularly in colder climates which is discussed in more detail in paragraph 4.4.2. The maximum dry period of the finishing layer is set to be 2 weeks. Assuming that (almost) dry periods can last for more than a month, the finishing layer should retain water for more than two weeks to fulfil this criteria. The upper boundary is less important, since a too wet quay wall is unlikely, due to evaporation and run off of abundant water. This paragraph only includes material modifications to obtain the correct moisture level in the finishing layer. System modifications to further increase the water retention behaviour of the finishing layer are not included in this paragraph, but can be found in chapter 9.

The ability of concrete to absorb and retain water is referred to as its water retention capacity. If the water retention capacity is high, the concrete will be able to retain more water after rainfall. The water retention capacity is related to the structure of concrete, which determines both its porosity and permeability. When concrete has a high permeability coefficient and porosity, water can easily enter the concrete and the concrete will retain more water due to the high contact area. However, a high permeability coefficient also means that the water immediately flows out of the macro-pores. In the situation that the macro-pores are not filled with soil, water is thus not stored in the macro-pores and is only retained in and at the surface of the aggregate and the cement paste. Therefore those two elements determine the water storage properties of the pervious concrete. The effect on the water storage properties of both elements is discussed in more detail in the following sections. As most applications of pervious concrete do not demand high water retention, literature on promoting the water retention is hardly available. However, literature for reduction of the water absorption can also be used for increasing the water absorption properties.

Aggregate
The water absorption of the aggregate material is directly related to the water absorption of the pervious concrete as long as the water is able to penetrate the cement paste layer coating the aggregates. Aggregate materials with interconnected pores, have the highest water absorption. Lightweight aggregates are porous, which means that the use of lightweight aggregates instead of normal aggregates increases the water absorption as long as the pores are interconnected. The maximum water absorption ($WA_{m}ax$) of lightweight aggregates may vary from a few percent up to 45%, depending on the aggregate pore structure (Domagała, 2015). A too open structure of the aggregates, might result in direct outflow of water, reducing the water retention capacity. However, with the cement layer coating the aggregates, direct outflow is probably prevented in the application of pervious concrete.

The aggregate properties of lightweight aggregates are highly depended on the formation of the aggregates. There are two types of lightweight aggregates: natural lightweight aggregates and artificial lightweight aggregates. Natural lightweight aggregates include amongst others vulcanic pummice, scoria and volcanic tuff. The pore structure of natural lightweight aggregates varies per type, but the previously mentioned natural lightweight aggregates have a high porosity with a significant share of open pores. This means that the pores are interconnected, resulting in high water absorption and permeability. Artificial lightweight aggregates include amongst others expanded clay, expanded shale, expanded slate, perlite, vermiculite and sintered fly ash. The artificial lightweight aggregates are divided in three sub groups based on the production method, namely expanded, agglomerated or foamed lightweight aggregates (Punkki, 1995). The first two manufactured aggregates are suitable to increase water absorption of pervious concrete as most of the pores in those aggregates are connected. Foamed lightweight aggregates consist of closed and small pores unsuitable for water absorption and are thus not recommended for increasing the water absorption capacity in pervious concrete.

Cement paste
The capillary pore structure of the cement paste is important for the permeability as discussed in paragraph 4.2.2.The WCR is influencing the capillary pore structure. In a mixture with a high WCR, more water is unused by the hydration process, leading to the formation of more capillary pores. In the investigation by Ye (2005) cement pastes with WCRs ranging from 0.4 to 0.6 are tested. This investigation showed that the effective porosity of a cement paste with a WCR of 0.6 is 23.0% which is twice as big as the effective porosity of a cement paste with WCR of 0.4 which is 11.3% at an age of 28 days. The permeability is $1.82\times10^{(}-11)$ m/s and $9.00\times10^{(}-14)$ m/s for a WCR of 0.6 and 0.4 respectively. The graph from Neville (1981) in Figure 4.3b also illustrates the positive relation between the WCR and the permeability.

4.3.2. Alkalinity

In the previous chapter it is concluded that a pH-value between 8 and 9 is suitable for the establishment of the selected plant species. It is important that the design of the substrate layer provides a living environment within this range over its whole life time. Therefore, the pH-value of the pervious concrete should be constant and within this range.

The initial pH-value of freshly casted concrete is very high. This is mostly due to the highly alkine cementitious material. Ordinary Portland Cement has an initial pH between 12 and 13 (Manso et al., 2014). Over its life time, the pH-value steadily reduces due to the process of carbonation. The process of carbonation in concrete consists of the following steps:

1. Diffusion of CO_2 through the gaseous part of the pores

2. Dissolution of CO_2 in water in the pores
3. Dissolution of $Ca(OH)_2$ in pore water
4. Reaction of $Ca(OH)_2$ and CO_2
5. Reduction in pH

The conclusion of the reference projects in paragraph 2.2 showed that an appropriate pH-value can be obtained in pervious concrete without the addition of additives due to natural carbonation. One of the tested plant species is Cymbalaria Muralis which is also part of the selected species for this investigation. In Table3.3 the pH-value optimal for this specie is found to be 8.5, which is in the middle of the range of the alkalinity. This implies that no extra measurements have to be taken to fulfil the ecological requirements regarding pH. However, for completeness of answering sub-question 2, promising methods of controlling the pH-value are presented. These methods might be useful when species favouring a lower pH-value are preferred.

The pH of concrete can be reduced in two manners: (1) reducing the pH-value of concrete after casting by means of accelerated carbonation or (2) changing the constituents of the binder the obtain a binder with a lower initial pH or increased carbonation properties. Accelerated carbonation is a process in which CO_2 sequestration (i.e., absorption of CO_2) is allowed to take place during curing of the concrete. This is an expensive solution and therefore the focus will be on second method. The second method uses alternative binding materials or supplementary materials to obtain a lower pH-value in the cementitious material. Rostami et al. (2021) investigated the pH value of CEM I, CEM II and CEM III and found that the pH is mainly related to the calcium concentration. The filtrate solution of CEM I has the highest pH of approximately 10 with a CaO content of 64.3% and the filtrate solution of CEM II has the lowest pH of approximately 9 with a CaO content of 43.5%. This implicates that CEM II is the best of these three types if a pH lower than 9 is required. Magnesium Phosphate Cement (MPC) and sulphoaluminate cement are both alternatives for OPC with a lower intial pH-value (Al-Tabbaa, 2013). Metakaolin is proposed for its ability to lower the pH. Metakaolin accelerates the natural carbonation reaction, lowering the pH to 9, whereas with pure cement the pH is 12 (Riley et al., 2019). Slag and fly ash also increase carbonation and thus reduce the pH-value.

4.3.3. Nutrients

In the previous chapter it is concluded that poor nitrogen availability is best for the desired vegetation, since other species prosper when more nutrients are available. It is important that the design of the substrate layer provides a poor nitrogen living environment over its whole life time.

An appropriate nutrient content at the start of the experiment is obtained by adjusting the soil mixture inserted in the pores of the pervious concrete to the poor nitrogen needs of the plants. When other nutrient ranges would apply, an appropriate environment can be obtained in the same manner by adjusting the nutrient availability in the soil. Details on the adjustment of the soil mixture are not part of this investigation since the focus is on the pervious concrete, but soil suppliers can be contacted to obtain an appropriate soil mixture.

The main challenge is the nutrient availability over time. Due to the use of nutrients by the vegetation and due to wash out, the nutrient level of the soil mixture changes. This can be explained by the theory of ”fertilizer moves with water”. When vegetation has established, nutrients are provided to the substrate in the form of degrading biomass. Due to the vertical orientation of the quay wall, root material is the only source of degrading biomass that is stored on the vertical surface. For vegetation demanding a poor nitrogen environment, this probably results in an appropriate circular environment with regard to nutrients, meaning that no maintenance in needed to keep the nutrient level at sufficient level when vegetation has installed in the starting phase of the quay wall. However, excessive nutrient availability can occur even without maintenance. Unfortunately, there are no design adjustments for the pervious concrete that prevent excessive nutrient availability if this has naturally occurred.

In case of failure of instalment of vegetation in the first phase of the quay wall, adjustments might be needed to ensure nutrient availability is maintained at correct level. Supplying fertilizer for the nutritional demands of plant growth is labor intensive and cost ineffective. The natural process of accumulation of nutrients on the rough surface of the pervious concrete, as was the process that stimulated the establishment of vegetation on old masonry quay walls, can be time consuming. Therefore some adjustments for the initial design of the quay wall are considered that provide nutrients to the plants. However, literature on the topic is limited, thus further research is needed when considering one of the adjustments.

- Urea (carbamide) is a common fertilizer and can be added to the mixture of pervious vegetation concrete to ensure nitrogen release by the pervious concrete. An increase in the urea dosage added to the planting concrete is beneficial for the nitrogen release rate. The 28-day cumulative release rate with 1.5 wt% urea is 50.4% according to Gong et al. (2018). It is also found that urea negatively affects the hydration of cement and increases fluidity. Due to the increase in fluidity there is a risk of pore blockage. The WCR of the mixture should be optimised accordingly to prevent increased fluidity. Furthermore, the compressive strength of the pervious vegetation concrete is reduced when urea dosage is more than 1.5 wt%. A positive side effect of urea is the reduction of the 28-day alkalinity of pervious concrete by 6.6% and the freeze-thaw resistance is improved by 12.4% with the addition of 4.4 kg/m^3 urea (Li et al., 2018). As the release rate for a period longer than 28 days is not investigated, more research is needed on that subject before the implementation of this adjustment. As 50.4% of the initial urea content is already released after 28 days, it is doubtful that the addition of urea can ensure appropriate nutrient release during service life.
- Using organic matter such as compost for partial replacement of fine aggregate in conventional concrete is studied by Muthulakshmi et al. (2021). Due to digestion of the organic matter, pores are created in the remaining material, which decreases the compressive strength and the density, but increases the water absorption. The nutrient release of the concrete is not investigated, but it is expected that nutrients are released due to the digestion of organic matter. In pervious concrete little to no fine aggregate is used, so replacement opportunities are limited in pervious concrete. The use of organic matter as extra filler can be considered but no literature is available on this subject. Further research would thus be needed when considering using organic matter in the mix design of pervious concrete.
- The use of biochar in pervious concrete as additive has been investigated in the application of vegetated pervious concrete. Biochar is a carbon-rich material produced from the thermal decomposition of organic material such as wood or agricultural waste. When applied in soil, biochar can increase the water retention capacity and the nutrient holding capacity. The addition of biochar to the mix design of the pervious concrete can therefore indirectly improve the substrate fertility (Tan et al., 2022). The biochar particles partly fill the macro-pores in the pervious concrete, thus reducing the porosity and improving the compressive strength. The biochar content should be balanced to obtain the minimum required porosity and appropriate nutrient conditions. In the investigation by Zhao et al. (2019) it appeared that a biochar content of 5 kg/m^3 is most suitable for vegetation concrete. Biochar can also be used to partially replace cement. In that case biochar has little to no impact on the porosity, but enhances water absorption and compressive strength when the biochar content remains below 6.5% (Qin et al., 2021).
- Fly ash is utilized in agriculture due to the presence of elements such as sodium, potassium, phosphorus and magnesium which can help improve the soil texture, water holding capacity, pH-value and nutrient content (Lu et al., 2023) (Hemalatha, Raj, et al., 2021). However, Kong et al. (2022) found a negative correlation between fly ash content in vegetation concrete and the plant height, indicating that the addition of fly ash has an inhibitory effect on plant growth. As the results of different researches are contradicting extra care should be taken when implementing fly ash in the mix design of pervious concrete to improve the nutrient availability.

4.3.4. Surface roughness and root ability

The factors surface roughness and root ability are interrelated. A pervious concrete sample automatically has a high (macro) surface roughness, due to its porous structure. When the parameter roughness is used, this can refer to different scales. The macro-scale refers to the ”waving” of the surface, while the micro-scale refers to the micro-roughness of the cement paste and the aggregate. Aggregate surface roughness, cement coating thickness and type of cement determine the micro-roughness. The surface morphology of concrete (macro-scale) is described by different parameters. Since no literature is found on the topic of surface roughness of pervious concrete, literature on exposed aggregate cement concrete is examined as the top layer of this type of concrete resembles the top layer of pervious concrete. The cement in the top layer of this type of concrete is namely removed to reveal the underlying aggregate. This creates a textured, visually appealing surface that is slip-resistant. Compared to pervious concrete the surface roughness is lower, since only the top layer of cement is removed leaving cement in the layer beneath, but the parameters effecting the macro surface roughness are expected to be similar. Gradation and maximum aggregate size influence the surface roughness of exposed aggregate cement concrete significantly (Wasilewska et al., 2018). This is in line with the parameters that increase the macro-porosity of pervious concrete, suggesting that there is a direct relationship between macro-porosity and macro-roughness. Therefore the parameters mentioned in paragraph 4.2.4 affecting the macro-porosity are also affecting the macro-roughness. When the macro-pores are filled with soil, the roughness at both scales is affected. Nonetheless, the soil is likely to be washed out from the surface, resulting in a roughness that is determined solely by the properties of the pervious concrete, the aggregate and the cement.

Root ability is also directly related to the connected macro-porosity. The interlinked pores namely form a network of open space in the concrete that can be reached by the roots. After casting of the pervious concrete, the open pores are filled with soil, which is important for nutrient and water retention. The soil does not hinder the growth of roots, so the focus is only on producing pervious concrete with the appropriate porosity. As is described in paragraph 4.2.4, the interconnected porosity is mainly influenced by the following parameters: the aggregate size, the gradation of the aggregates, the cement content and the compaction energy. In the reasearch by Soltani (2022) the minimum porosity percentage of 18% is reached for almost all mixtures made with 8 mm aggregates for a WCR ranging from 0.32 to 0.38 and a cement content ranging from 350 to 550 kg/m^3. For a cement content of 350 kg/m^3 the percentage of 18% is again reached for almost all mixtures independently from the aggregate size (ranging from 2.83 mm to 8 mm) and the WCR (ranging from 0.32 to 0.38). In this research compaction is done by applying rodding when filling the mold. Akkaya and Çağatay (2021) also found a porosity value above 18% for mixtures made with aggregate size of 8 to 16 mm, which leads to the believe that this fraction is often appropriate, when combined with an appropriate cement content and compaction method.

4.4. Material properties related to the technical requirements

4.4.1. Strength

The 28-day compressive strength of pervious concrete usually lies in the range of 8 to 30 MPa, as is mentioned in paragraph 4.1. For porous materials, the strength is highly affected by its porosity, since the load-carrying capacity is provided by the solid material. Nassiri and AlShareedah (2017) showed with a sensitivity analysis that changing the porosity has a more significant effect on the compressive strength than changing the WCR or the cement content. The relationship in equation 4.1for the porosity and the previously mentioned parameters is suggested. It is valid for aggregates with a maximum aggregate size of approximately 10 mm, porosity ranging from 13 to 42%, WCR ranging from 0.14 to 0.4 and cement content ranging from 150 to 413 kg/m^3. This results in a 28-day compressive strength of 13 MPa for a porosity of 18%, a WCR of 0.4 and a cement content of 350 kg/m^3.

$$f_c = 25.38 - 0.5392P - 13.12WCR + 0.00762C \tag{4.1}$$

with:
f_c = 28-day compressive strength (MPa)
P = porosity (%)
WCR= water-to-cement ratio ($-$)
C = cement content (kg/m^3)

The test results of the investigation of Yu et al. (2019b) showed that the compressive strength increases rapidly with an increase of aggregate size till an aggregate size of 7 mm by same porosity. Beyond that point the compressive strength decreases. Therefore the 28-day compressive strength of 13 MPa, will be a bit lower when a fraction of 8/16 mm is used as the maximum aggregate size is then higher then the range which is set equation 4.1. An increase of thickness of the cement paste, increases the compressive strength up till 1.15 mm and becomes stable after that (Yu et al., 2019b).

The strength properties can be improved by adding sand to the pervious concrete mix. This effects the void ratio, since the small particles of sand fill up the pores of the pervious concrete and increase the contact area of the aggregate particles with the cement paste. Sand or another filler can only be added if the minimum value of connected porosity is still obtained. The same applies for increasing the compaction effort. This results in strengthening of the pervious concrete, but reduces the porosity, so these two properties should be carefully balanced (Sonebi et al., 2016). Increasing the strength can also be done by partially replacing cement paste with alternative materials such as fly ash, metakaolin, silica fume or blast furnace slag. These admixtures can strengthen the matrix of the pervious concrete mix by increased calcium silicate hydrate (CSH) gel formation. Furthermore, the WCR should be around 0.4 for optimal strength properties according to the research done by Taheri et al. (2021)

The replacement of ordinary coarse aggregate by lightweight coarse aggregate such as pumice aggregate, reduces the compressive strength to a range of 1.8 to 5.99 MPa. It is noted that failure of the lightweight aggregate samples occurred by rupture of the aggregate (Tang et al., 2022). Improving the compressive strength of pervious concrete with lightweight aggregate can thus not be done by improving the bond strength between the aggregates and can only be done by decreasing the porosity of the pervious concrete, to increase the volume of aggregates.

4.4.2. Durability

Previous research recommends that pervious concrete has the ability to reach a service life of up to 20 years depending on its application (Sonebi et al., 2016). In the paper by Kia et al. (2017) a service life ranging from 6 to 20 years is mentioned. The end-of-life of pervious concrete is usually caused by clogging, freeze-thaw degradation or excessive surface raveling. In the application as vegetated concrete, failure due to clogging is irrelevant, since the material is clogged from the start, due to the soil that is added to the pores of the pervious concrete to initiate growth of vegetation. The last two failure principles are more relevant and will be elaborated further.

Freeze-thaw durability

Water expands by 9% upon freezing. As long as there is enough expansion space for the freezing water no problems occur. However, if the water is entrapped, it causes high pressures. This principle occurs inside (partly) saturated concrete during FT cycles and causes internal stresses that eventually result in deterioration. Deicing salts have a negative effect on the freeze-thaw durability of concrete, since they reduce the freezing-point of water. The concentration of deicing salts decreases with depth in conventional concrete causing a freezing-point gradient in the concrete. Combining the freezing-point gradient with the naturally occurring temperature gradient, the surface and the inside of the concrete will freeze leaving an unfrozen water layer in-between. When the water in the in-between layer freezes this will lead to high pressures due to entrapment of the water between two frozen layers. This results in exfoliation of the surface layer, better known as scaling. A visualisation of this phenomenon is shown in Figure 4.4 (Betonhuis, 2020). This phenomenon can occur in pervious concrete as well, resulting is scaling of the cement paste layers.

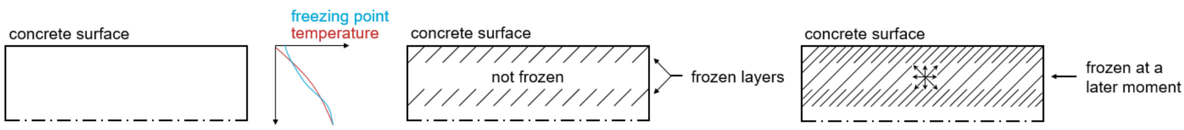


Figure 4.4: Visualisation of the scaling phenomenon occurring with deicing salts in conventional concrete

The main parameters affecting freeze-thaw durability of pervious concrete are the macro-porosity, the particle contact area, the aggregate type and the WCR. Furthermore, the degree of saturation and the air entrainment determine if sufficient expansion space is available, which is an important factor for the freeze-thaw durability (Taheri et al., 2021).

The void ratio directly influences the freeze-thaw durability (Kevern and Schaefer, 2013). As discussed before, the void ratio is related to many factors, most importantly the aggregate size, aggregate size distribution and the level of compaction. Fine aggregate can thus promote freeze-thaw durability. This improvement is not only related to a reduction in porosity, but is also related to the increase in particle contact area, which improves strength and durability (Kevern and Schaefer, 2013). Taheri et al. (2021) found that replacing 8% of coarse aggregate with sand improved freeze-thaw durability. Reducing the course aggregate size from 16 mm to 4.75 mm enhanced the number of FT cycles 20 times according to Liu et al. (2018).

Research has indicated that freeze-thaw deterioration is directly related to the aggregate type and more specifically to the water absorption capacity of the aggregate. The water absorption of the aggregate should be less than 2.5% for the production of durable mixes. In that case the reduction in the relative dynamic modulus of elasticity and the mass loss do not exceed the limit boundary (Kevern et al., 2010).

In contrast to conventional concrete, an increased WCR improved freeze-thaw durability in the experiments of Taheri et al. (2021). The experiments used WCR's below 0.4, so this statement is valid till the limit of 0.4.

As discussed before, expansion space is important for the freeze-thaw resistance of concrete. That is why air-entraining agents are added to conventional concrete to increase the freeze-thaw durability. These agents stimulate the formation of micro pores, which are pores with a diameter of less than 300 micro meters. The space between the entrapped air voids may not be too big, since the expanding freezing water should be able to reach the air voids. The air-entraining agent is only effective if the distance between the voids is less than 250 micro meters (Betonhuis, 2020). Yang et al. (2006) showed that air-entraining agents impact the freeze-thaw durability of pervious concrete significantly by increasing the number of cycles until failure from 100 without air-entraining admixture to 300 with air-entraining admixture. Other admixtures that can increase the freeze-thaw durability are the addition of fibers and using internal curing agents (Kevern and Schaefer, 2013).

Complete saturation of the pervious concrete accelerates damage due to FT cycles (Yang et al., 2006). In the most commonly known application of pervious concrete as permeable pavement, saturation conditions rarely occur. However, in the application as quay wall, the lower region will be completely saturated due to the direct contact with canal water. Furthermore, clogging of the pervious concrete may induce damage due to FT cycles, since drainage capacity is reduced. This could be a problem in the application as a vegetated concrete, since the pores are filled with a soil mixture directly from the start (Olek et al., 2003).

4.5. Conclusion

In chapter 3, the requirements of a vegetated quay wall are determined. In this chapter, the material properties of pervious concrete are reviewed to determine if those requirements can be met by the substrate layer on material level.

First of all, to meet the moisture requirement two alterations are proposed. The use of light-weight aggregates is recommended to adjust the water absorption capacity of the aggregate material. Additionally, increasing the WCR is recommended to adjust the porosity of the cement layer to ensure water is able to flow through the cement layer to the aggregate material. As there is no research quantifying the effect of the proposed measures, it should be investigated to what extend the substrate layer can fulfil the moisture requirement, whilst fulfilling the porosity, strength and durability requirements. Part II focuses on the effect of these measures on the water absorption properties. From the literature research in this chapter and the information in paragraph 2.2 it is concluded that no alterations to the pervious mix design are needed to fulfil the alkalinity requirement, as the natural carbonation process is quickly reducing the pH level of pervious concrete to a suitable level for the selected plant species.

This requirement is thus fulfilled on material level due to the high porosity of pervious concrete. The literature that is reviewed for the nutrient availability in pervious concrete showed that appropriate conditions can easily be obtained at the start of the experiment by adjusting the soil mixture added to the pervious concrete. The nutrient availability on the long term can be a problem, when installation of vegetation in the first period has not occurred. Although some additives and partially replacement materials are proposed in this chapter, knowledge on these methods is limited and more research is needed to determine the potential of these alterations. However, those alterations are not further investigated in this research as nutrients can also be provided to the quay wall due to accumulation of nutrients on the rough surface. This might be a time-consuming process, but it has been proven possible in the traditional masonry quay walls and this requirement in thus not prioritized. Last of all, the interconnected porosity, which is associated to both the surface roughness requirement and the root ability requirement, can be obtained in pervious concrete by applying coarse aggregates in the fraction 8/16 mm. This fraction should be combined with an appropriate cement content and compaction method. For a WCR ranging from 0.32 to 0.38, a cement content ranging from 350 to 550 kg/m^3 is suitable to produce a pervious concrete with a interconnected porosity higher than 18%. An appropriate cement content is not investigated for higher WCRs, so further research is needed to determine a suitable cement content for mix designs with increased WCRs.

The technical requirements can be reviewed on material level, as the requirements are boundaries for the pervious layer. Literature research showed that the compressive strength of pervious concrete is mainly depended on the porosity of the material. The calculated 28-day compressive strength of 13 MPa for a porosity of 18%, a WCR of 0.4, a cement content of 350 kg/m^3 and a maximum aggregate size of 10 mm is far above the strength requirement. Although the fraction 8/16 mm will result in a slight reduction of the strength, the expectation is that a mix design conform the previously mentioned parameters, reaches the compressive strength requirement. That an increased WCR results in a lower compressive strength is mentioned in literature, but the reduction is not quantified for WCRs above 0.4. The experimental part should thus investigate if mix designs with higher WCRs can fulfil the compressive strength requirement. The use of lightweight pumice stone aggregate is expected to reduce the compressive strength significantly. For pumice stone aggregate failure most likely occurs due to breakage of the aggregate and strength can thus not be improved by partially replacing cement paste to increase the strength of the paste. For improving the compressive strength of pervious concrete with pumice stone aggregate, increasing compaction energy or the use of fillers can be considered if the compressive strength is proven to be insufficient. Although the freeze-thaw durability is important, no boundary value is set for the maximum mass loss during FT cycles. The aggregate type, the WCR and the porosity all influence the resistance to FT cycles, but quantitative data is not provided in literature. It is therefore important to determine the impact of those parameters on the freeze-thaw durability in the experimental part. The results have to prove if the mix design can be used as pervious layer. The service life of the pervious concrete is in the range of 20 years, which suggests that intermediate replacement or repair measures are needed.

II

Material Modification

5
Experiments

The ecological requirement of the humidity level in the finishing layer is the focus point of the experimental part of this thesis. The mix design of the pervious concrete layer is thus adapted to improve this property. The other ecological requirements are not tested in this part of the investigation, apart from the macro-porosity which should be at least 18%. The goal is to find the alternative with the best water storage properties whilst fulfilling the strength and durability demands.

5.1. Material modification & hypotheses

As discussed in paragraph 4.3.1, the water storage properties of pervious concrete are depending on the type of aggregate and the porosity of the cement paste. The hypotheses is that increasing the water absorption capacity of the pervious concrete is mostly determined by the water absorption capacity of the coarse aggregate material. However, it is expected that the coarse aggregate material is only able to absorb water if the permeability of the cement paste layer is increased.

Lightweight aggregates are chosen to improve the water absorption of the aggregate material. Two types of natural lightweight aggregates are chosen for the experimental phase. The first type is lava stone, which is already used in the mix designs that are tested by the company. Additionally, pumice stone is chosen, due to its low density and its higher SSD water absorption ratio compared to lava stone. As is seen in Figure 4.3b, the permeability of cement paste increases exponentially when increasing the WCR. Therefore different WCRs are used to adapt the permeability of the cement paste. A stabilizer is added to the mixtures with a WCR above 0.4 to ensure appropriate fluidity of the cement paste. The stabilizer that is used is a mixture of micro-cellulose fibres derived from sugar beets and water. Additionally, an admixture for increasing the internal cohesion can be added. The WCR of 0.4 is reviewed as the reference mix design as this is the WCR that is within the normal boundaries for pervious concrete.

Proposed hypotheses about how the type of aggregate and the WCR of cement paste affect water storage properties have been tested through experiments to determine their validity. When referring to the water storage properties, the following three properties are meant: water storage capacity, water absorption rate and water release rate. These properties together provide information on the water availability in pervious concrete over time. Apart from the water storage properties, the mechanical performance and the durability of the samples is tested. Since the pervious concrete layer does not have a structural function the mechanical requirements are low, but are still checked for completeness of the research. Furthermore, a freeze-thaw test should be performed since there is a high risk of failure due to the macro-porosity of the concrete and the micro-porosity of the cement paste.

5.2. Research methodology

5.2.1. The experimental method

The experimental research is focused on three components: the aggregate material, the cement paste and the macro-pores. Together these three components form the final product: a pervious concrete. At first the components are tested individually to determine basic material properties of each component and eventually the different components are combined to make the final product, which is again tested to determine the properties of the pervious concrete. Properties are thus determined on different scales. An overview of the experimental method is given in Figure 5.1. The procedure for all the experimental steps is described in paragraph 5.3.

Aggregate
Test are conducted on the raw aggregate material to provide accurate information on the properties of that specific batch. The following tests are performed on the raw aggregate material:

- Determination of the particle density and the water absorption

Cement paste
The cement paste samples are tested to determine the basic material properties and strength properties. Since the pervious concrete consists solely of coarse aggregate and cement paste, these properties are critical for the properties in the final pervious concrete samples. The following properties will be defined by tests performed on cement paste:

- Determination of the setting time
- Determination of the flexural strength
- Determination of the compressive strength
- Determination of the water absorption and evaporation
- Determination of the pore structure by CT scanning

Additionally, experiments on cement mortar are done to compare the strength properties of the paste samples to the strength properties of the mortar samples, since values in literature are primarily focused on cement mortar. As the final pervious concrete samples do not contain sand, other properties of cement mortar are not important for this investigation. Cement mortar will thus solely be tested on the following properties:

- Determination of the flexural strength
- Determination of the compressive strength

Pervious concrete
When all components are combined this results in pervious concrete. Therefore this part of the investigation is done on multiple mix designs for pervious concrete. It is determined which parameters influence the properties in the most beneficial way. Additionally it is determined if one of the tested mix design is suitable for the pervious concrete layer of the quay wall elements. The following tests are done to determine the effect of each design parameter on those properties:

- Determination of the connected porosity
- Determination of the compressive strength
- Determination of the water absorption and evaporation
- Determination of the freeze-thaw resistance

Macro-pores filled with substrate
Experiments cannot be conducted on macro-pores as individual component. Instead the experiments are performed on pervious concrete mix designs including all elements (aggregates, cement paste and macro-pores). Apart from determining the porosity of the pervious concrete samples, which is part of the previous section, the addition of substrate with glue to the macro-pores is investigated. The following tests are performed on the pervious concrete with substrate:

- Determination of the water absorption and evaporation

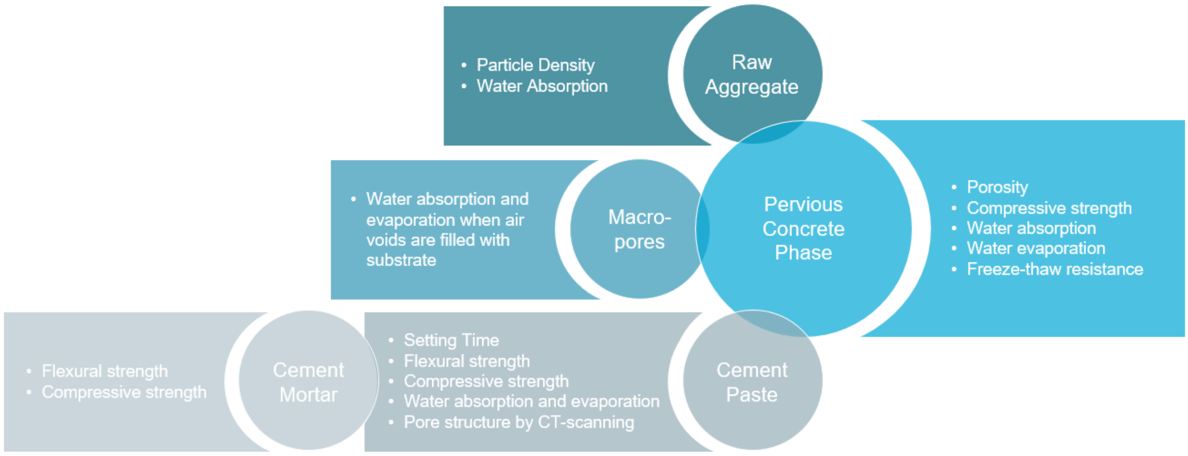


Figure 5.1: Overview of the experimental method. Pervious concrete consists of three major elements as is visualised. The properties of these elements is determined in separate tests, to finally combine the different elements in pervious concrete tests. As the results of the cement paste samples are inconclusive, cement mortar is tested to validate the cement paste results.

5.2.2. The Taguchi method

The Taguchi method, designed by Dr. Genichi Taguchi, uses an orthoganal array approach, which can be used to simplify the testing procedure for problems with a large amount of variables. Instead of testing all possible combinations of factors (as in the full factorial design method), the Taguchi method tests pairs of combinations, to verify the effect of the individual factors on the output. Applying this method thus reduces the amount of experiments needed, whilst still accurately determining which factors affect the product quality the most. This is useful since experiments take time, cost money and available space and devices for experiments are limited. In this research the Taguchi method is used to reduce the number of samples in the first series of pervious concrete. The goal of these experiments is to optimize multiple variables, which would result in many samples with the full factorial design method.

The Taguchi method is a procedure, consisting of the following general steps:

1. Define the objective

   The process objective is a performance measure. In this research the primary process objectives are to maximize the water absorption capacity and rate and to minimize the water evaporation rate. The secondary objectives are to maximize the compressive strength and the freeze-thaw durability.

2. Identify factors influencing the performance characteristics

   The factors influencing the performance characteristics are discussed in chapter 4. The following factors are mentioned: the aggregate type, aggregate size, the aggregate gradation, the WCR, the ACR and the level of compaction. Furthermore, the performance is influenced by the sample size, the curing time, the curing humidity and temperature and the environment in which the tests are performed.

3. Determine the design parameters

   The design parameters are expected to impact the process objectives and are varied in the mix designs. Other parameters are kept constant in all mix designs to ensure that they do not impact the results. Understanding of the process in necessary, to determine appropriate levels for each variable. In Table 5.1 the number of series needed for different numbers of parameters and different numbers of levels can be found. In this case 3 two-leveled variables are tested, so instead of 8 series a research with 4 series suffices. The chosen design parameters are the aggregate type, which is a qualitative variable and the fraction of the aggregate and the water-to-cement ratio (WCR), which are both quantitative parameters (Table 5.2).

Table 5.1: Reduction of the number of experiments when using the Taguchi approach

Number of factors	Number of levels	Number of experiments	
		Full factorial	Taguchi
3	2	8	4
7	2	128	8
15	2	32 768	16
4	3	81	9
13	3	1 594 323	27

Table 5.2: Factors that are varied with the Taguchi method and the levels on which the factor is varied

Design parameters	Levels	
Aggregate Type	Type I: Pumice Stone	Type II: Lava Stone
Aggregate Fraction	Small: 8 / 11.2	Big: 11.2 / 16
WCR	Low: 0.6	High: 0.8

4. Create orthogonal array

   Knowing the number of parameters and the number of levels, the proper orthogonal array can be selected. In this case the appropriate orthogonal array is the L4 Array. In Table 5.3 the L4 array that is used for the first series of pervious concrete is shown.

5. Conduct the experiments

   The experiments are conducted on all the series indicated in the array to collect data on the effect of the parameters on the performance measures. For each experiment an appropriate number of repetitions is chosen, to increase the validity of the results. For example the water absorption experiments are conducted on 3 cubes of the same mixture, thus 3 results per series are obtained for this performance measure. In Table 5.3 the results Ti,j are included where i is the series number and j is the trial number.

6. Analyze the data

   For analysis, the effect of each design parameter should be determined. The method uses a signal-to-noise (S/N) ratio to calculate the effect. A higher S/N ratio, indicates that the series is performing better for the investigated objective. Depending on the investigated objective, the goal might be to minimize or to maximize this objective, resulting in two signal-to-noise ratio formulas:

   - For minimizing the objective

$$S/N_i = -10\log(\frac{1}{N} \cdot \sum_{i=1}^{n} T_{i,j}^2) \tag{5.1}$$

With i = series number, j = trial number and N = number of trials.

Table 5.3: Taguchi's orthogonal array for the pervious concrete samples of the first series

Serie No.	Aggregate Type	Aggregate Fraction	WCR	Result 1	...	Result N	S/N
C1.1	Pumice Stone	8 / 11.2	0.6	$T_{1,1}$	...	$T_{1,N}$	S/N_1
C1.2	Pumice Stone	11.2 / 16	0.8	$T_{2,1}$	...	$T_{2,N}$	S/N_2
C1.3	Lava Stone	8 / 11.2	0.8	$T_{3,1}$	...	$T_{3,N}$	S/N_3
C1.4	Lava Stone	11.2 / 16	0.6	$T_{4,1}$	...	$T_{4,N}$	S/N_4

- For maximizing the objective

$$S/N_i = -10\log\left(\frac{1}{N}\cdot\sum_{i=1}^{n}\frac{1}{T_{i,j}^2}\right) \quad (5.2)$$

Once the S/N value of each series is determined, resulting in four S/N ratios as illustrated in the last column of Table 5.3, the average S/N for each parameter is calculated. The influence of each parameter should be investigated by calculating S/N values for both levels of one parameter. The S/N values per level can be calculated with the S/N values of the series that contain that specific level. For example the S/N value of the aggregate type ”Pumice Stone” is calculated with the S/N values of series 1 and 2, according to equation 5.3. In contrast, the S/N value of the aggregate type ”Lava Stone is calculated with the S/N values of series 3 and 4, according to equation 5.4, since those series use lava stone instead of pumice stone.

$$S/N_{1,1} = \frac{S/N_1 + S/N_2}{2} \quad (5.3)$$

$$S/N_{1,2} = \frac{S/N_3 + S/N_4}{2} \quad (5.4)$$

Table 5.4: Overview of S/N per parameter for an L4 array

Level	Parameter 1	Parameter 2	Parameter 3
1	S / N $_{P1,1}$	S / N $_{P2,1}$	S / N $_{P3,1}$
2	S / N $_{P1,2}$	S / N $_{P2,2}$	S / N $_{P3,2}$
Δ	...	...	...

The same principle can be applied on both levels of the other two parameters, and all values can be tabulated according to Table 5.4. The difference between the two S/N values per parameter is indicated with the symbol delta Δ. A high delta indicates a high influence of that design parameter on the process objective. This is due to the fact that a small change in the signal causes significant change in the output variables. When using the level corresponding to the highest S/N value, the best outcome is expected for that specific objective. In this way, all parameters can be optimized. A ranking can be made based on the delta, where the lowest rank is equivalent to the lowest delta meaning the parameter has least influence and the highest rank corresponds to the highest delta indicating the parameter had the most influence. The results can be put in a graph with Taguchi trendlines to visualize the impact of each parameter on the objective of concern. These trendlines enable the indication of promising mix designs for optimization of the objective of concern.

5.3. The experimental procedure

The procedure selected to collect the data should be consisted throughout the complete research. A deductive approach is used to validate the hypotheses.

5.3.1. Starting point

The starting point of this research is the mix design proposed by Holcim Group in Lyon. The recipe of this mixture is included in Table 5.5. This mixture is chosen, since this mixture is extensively tested in the laboratory in Lyon and the mixture is also at the base of the vegetated porous wall elements that are produced by Holcim in Oudenbosch. It showed promising results in the laboratory and outside the laboratory in Lyon with regards to vegetation in an irrigated environment. The mixture is adapted to hopefully create a self-sustaining vegetated pervious concrete layer. For this reason certain parameters that are expected to affect the water characteristics are varied on certain levels. The testing parameters are the aggregate type, the aggregate fraction and the WCR. More information on the testing parameters can be found in paragraph 5.2.2.

Table 5.5: Mix design for 1m^3 of pervious concrete from Lyon

	Density [kg/L]	Mass [kg]	Volume [L]
Efficient water	1.000	Confidential	Confidential
Supplementary water (absorption by aggregate)	1.000	Confidential	Confidential
Main cement (CEM III/B 42.5)	2.990	Confidential	Confidential
Additional cement (CEMI 52.5 R)	3.130	Confidential	Confidential
Dry aggregate (Lava 4/16)	2.580	Confidential	Confidential
Admixture (Cugla HR-6)	1.040	Confidential	Confidential
Air (medium compaction)	-	-	Confidential

Pre-wetting the aggregates
In the recipe from Lyon dried aggregate is used. Because of the water absorption of the aggregate, supplementary water is added, based on the water absorption ratio after 24h. Water absorbed by the aggregates is namely not available for the hydration of cement as explained in paragraph 4.2.2 and water absorption by the aggregates also causes poor workability of the concrete mixture. For casting of the samples in this experiments, the aggregate is not dried beforehand. Instead the aggregate is pre-wetted by immersion in water 1 day prior to casting. Just before casting the aggregate material is drained and the surface of the aggregate is dried resulting in saturated surface dry (SSD) particles. The described process obviates the need to include supplementary water according to the water absorption characteristics of the aggregate. However, the mass of the dry aggregate should be adjusted to a wet mass based on the 24h water absorption of the aggregate. It must be noted that it is difficult to achieve a constant quality of the pre-wetted aggregate, as removing surface water to obtain SSD conditions is prone to experiment error.

Adjusting aggregate fraction
Aggregates in the fraction ranging from 4 to 16 mm are used in the original recipe. However, for the samples in the experiments in this research the aggregate fraction is adapted. The finer aggregates between 4 mm and 8 mm are completely removed and depending on the series of the mix design a fraction 8/11.2 mm, 11.2/16 mm or 8/16 mm is used. This choice is based on the available fractions of the raw materials in the industry. The narrower gradation with respect to the original recipe can effect the porosity and the aggregate surface area, which could adjust multiple properties compared to the original mixture as explained in the previous chapter.

Adjusting aggregate type
Lava stone is used as coarse aggregate in the mix design of Lyon. In the experiments conducted in this research both lava stone and pumice stone are used. To be able to adjust the mixture for both aggregate types, the volume of the aggregate is kept constant, adjusting the mass based on the density of the material. The fact that the fraction that is used deviates a bit from the original mixture is not taken into account for the volume of the aggregate per m^3 of concrete.

Adjusting WCR
The WCR of the mixture is based solely on the efficient water added to the mixture, so the water which is absorbed by the aggregate is not taken into account when determining the WCR. This results in a WCR of 0.26, which is much lower than the values that are used in this research. In the original mix design, the super plasticizer Cugla HR-6 is added to improve the workability of the mix. Because of the higher WCRs, no super plasticizer is added in the mix designs in this investigation. Instead an admixture is added to reduce the fluidity of the cement paste. More information on this admixture will be provided later on. The cement paste volume is kept constant in all the mixtures, but the ratio between cement and water is varied. This results in lower amounts of cement which might negatively impact strength and durability properties.

5.3.2. Materials
As explained in paragraph 5.2.1 the properties are tested in different phases. The samples are composed of coarse aggregates, sand, cement, admixtures and micro-fibres depending on the testing

phase. A mixture of soil, glue and tap water is added to the macro-pores of the series tested with soil. In this paragraph all materials are discussed in more detail.

Coarse aggregate

Two types of aggregate are used in this research: Pumice stone and Lava stone. The pumice stone is mined in Suðurland, a region in the south of Iceland. It is provided by H&B Grondstoffen in the fraction 0/31.5 and the material is sieved to obtain the appropriate fraction. The material is characterized by a low density and great water absorption. It is primarily used as light weight filling material, but the possibility of using it in the application of pervious concrete is investigated in this research. The second aggregate type is lava stone which is also a lightweight aggregate material, but has a much higher density compared to pumice stone. It also has a porous structure, but the water absorption of lava stone is lower. The lava stone that is used is Porodur® Lava which is mined in the area northwest of Koblenz, in the state of Rhineland-Palatinate (Germany). The material is available at H&B Grondstoffen in several gradations. For the experiments the fraction 8/16 is used. To separate the 8/11.2 fraction from the 11.2/16 fraction for making the first series of pervious concrete, the aggregate material is sieved. For the second series not all aggregate material is sieved. Instead a representative specimen is sieved to determine the particle size distribution of the lava stone aggregate, which is included in Figure 5.2. Properties of both aggregate types provided by H&B Grondstoffen are included in Table 5.6.

Table 5.6: Material properties of the aggregate materials utilized in this investigation

	Pumice Stone (0/31.5)	Lava Stone (16/32)
Bulk weight [kg/m^3]	~ 500	~ 1050
LA value [%]	35	<40
CBR value [%]	>25	>50
Angle of internal friction [°]	>45	>45
Aggregate form	Rounded	Angular

As the dry particle density and the water absorption of the aggregates are not provided by H&B Grondstoffen, these properties are determined conform NEN-EN 1097-6:2022. According to Annex C, the recommended testing method for coarse lightweight aggregate particles is the pyknometer method. The results of the pyknometer tests for the density and the water absorption are included in Table 5.7 and Figure 5.3, respectively. The standard deviations are based on 2 repetitions of the test per aggregate type.

The dry particle density of lava stone is approximately 3 times the dry particle density of pumice stone. As coarse aggregates are the main component of pervious concrete, the difference in density is strongly related to the difference in density of the pervious concrete. The water absorption of pumice stone aggregate is much higher than that of lava stone aggregate, especially when looking at the mass-%. However, the water absorption per unity volume is more suitable for fair comparison because of the different densities. It is concluded that pumice aggregate absorbs 3.6 times more water than the same

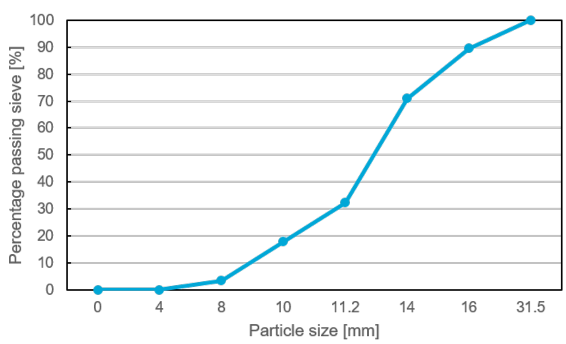
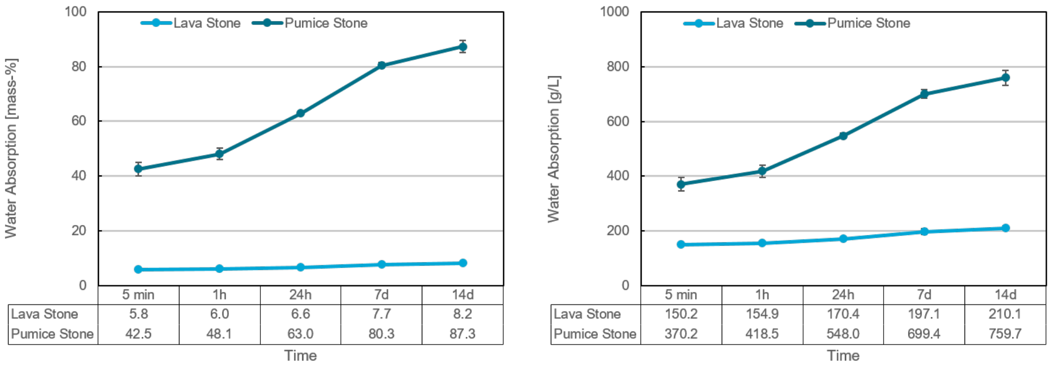


Figure 5.2: Particle size distribution of used lava stone aggregates in the mix design of the second series

Table 5.7: The dry particle density of the coarse aggregates

	Apparent particle density [g/L]	Standard deviation [g/L]
Lava Stone	2574.2	42.2
Pumice stone	870.4	8.1



(a) mass-%

(b) g water / L aggregate

Figure 5.3: Water absorption of the coarse aggregate materials

volume of lava aggregate. As the aggregate volume in the pervious concrete samples is assumed constant, the difference in water absorption expected for the pervious concrete is in the same order of magnitude. This is only valid when the cement paste coating is not reducing the water absorption of the aggregate.

Cement and admixtures

For this research CEM III/B is used. The standard type available at the TU Delft is CEMIII/B 42.5, having normal strength development. The material chemical composition of the cement is shown in Table 5.8. Furthermore, the water retaining admixture Cugla Colloidal 100 is used to increase internal cohesion in the mix designs of the second series.

Micro-cellulose fibers

Micro-cellulose fibres from sugar beets are used as a stabilizer in the mix designs with a WCR higher than 0.4. The product that is used is called Betafib MCF and consists of cellulose (60%), pectin (0.5 - 10%) and hemicellulose (1-15%) with a typical particle length in the range of 25 - 75 μm and a particle diameter in the order of magnitude of 0.1μm. The micro-cellulose fibres lead to a built up in the viscosity of a liquid due to the physical network the fibres form and can thus be used to improve the workability of

Table 5.8: Chemical composition of CEM III/B N

	Percentage [%]
CaO	47.3
SiO_2	29.2
Al_2O_3	9.4
Fe_2O_3	1.9
MgO	5.1
Na_2O-eq	0.81
SO_3	2.7
Cl^-	0.06
Loss of ignition	1.7
Insoluble residue	0.4

cement pastes with a high WCR. The fibres are added by replacing the mixing water for a Betafib-water mixture with 0.5% of Betafib. This means that the exact amount of fibres is depended on the WCR, but the ratio between Betafib and water is kept constant for all samples that include the stabilizer.

Sand
Sand is only used in the cement mortar samples. According to EN 196-1 CEN Standard sand should be used for the compressive and flexural strength testing of the mortar samples. The particle size distribution of CEN Reference sand should lie within the limits given in Table 5.9. Since the sieve gradations in which sand is available at the TU Delft differed from the mesh sizes used for CEN Reference sand, the particle size distribution had to be adopted, but it is attempted to resemble the particle size distribution of CEN Reference sand. The particle distribution of the sand that is used is given in Table 5.10.

Soil mixture
The mixture of soil that is added to the macro-pores is made of soil (by BVB Substrates), with the addition of a biological binder (Goedemorgen! 12ZR by Groenemorgen) which functions as glue in proportion 5:1 in volume. Constituents of the binder are confidential. Tap water is added to the mixture to make the soil mixture sufficiently fluid for pouring into the macro-pores in a vacuum tank.

5.3.3. Series and mix designs
Three different stages are distinguished for testing:

Cement paste and mortar
Four different cement paste mix designs and corresponding cement mortar mix designs are tested in the first stage. The varying parameter is the WCR. Additionally, the mix design with a WCR of 0.4 is tested with and without the addition of micro-cellulose fibers to determine the effect of the fibers on the properties of the cement paste. The mix designs for both the cement paste samples and the cement mortar samples are given in Table 5.11.

Pervious concrete
The testing of the pervious concrete phase consists of two series. The first series contains four mix designs which are created with the Taguchi method. Results of this first series, should thus be analysed accordingly. Based on the results of this first series, a second series of pervious concrete is tested consisting of three mix designs. As only one parameter is varied in this series, full factorial design is used instead of Taguchi design.

In Table 5.12 an overview of the constiutents of the mix design of the first series is given. For the first series of pervious concrete two types of aggregates are chosen due to the expected difference in water absorption. The hypotheses is that the use of the pumice aggregate, results in a higher water absorption of the pervious concrete sample, due to the higher water absorption of the aggregate itself. However, if the cement paste coating is not water permeable, no difference is expected between the water absorption of the pervious concrete with the two types of aggregates. As the WCR levels used in the first series of pervious concrete samples are 0.6 and 0.8, the cement paste is expected to be permeable, which would result in a higher water absorption when pumice stone aggregate is used instead of lava stone aggregate. Other properties such as the compressive strength and the freeze-thaw durability should indicate if increasing the water absorption capacity of pervious concrete by increasing the water absorption of the aggregate, is possible whilst fulfilling the strength and durability demands.

The second series is not varying the aggregate type. Lava stone is used for the samples in the second series. The WCR is varied in the range of 0.4 to 0.8. An overview of the constituents of the second series are given in Table 5.13. The hypotheses is that the samples with a WCR of 0.4 can hardly absorb

Table 5.9: Particle size distribution of the CEN Reference sand

Square mesh size [mm]	2	1.6	1	0.5	0.16	0.08
Cumulative sieve residue [%]	0	7 ± 5	33 ± 5	67 ± 5	87 ± 5	99 ± 1

Table 5.10: Particle size distribution of the sand used for the mortar samples

Square mesh size [mm]	2	1	0.5	0.25	0.125
Cumulative sieve residue [%]	0	33	67	83	100

Table 5.11: Properties of series for the cement paste samples (P) and the cement mortar samples (M)

Serie No.	WCR	Stabilizer
P_REF	0.4	No
P_0.4	0.4	Yes
P_0.6	0.6	Yes
P_0.8	0.8	Yes

Serie No.	WCR	Stabilizer
M_REF	0.4	No
M_0.4	0.4	Yes
M_0.6	0.6	Yes
M_0.8	0.8	Yes

water due to the low water permeability of the cement paste layer with a WCR of 0.4. Furthermore, it is tested if the compressive strength and durability demands can be reached with a mix design with porous aggregate material.

Pervious concrete with soil
One of the mix designs (C1.4) from the first series of pervious concrete is tested in combination with soil. Both fine and coarse soil are tested, resulting in the test series from Table 5.14. The effect of the addition of soil to the macro-pores of pervious concrete on the water absorption properties is investigated. The hypotheses is that the samples with soil have a higher water absorption capacity than the samples without soil, as water is better retained in the pores with soil. Furthermore, the water absorption rate is expected to be higher for the samples with soil because of the capillary effect in the soil. As fine soil can more easily be added to the macro-pores, it is expected that fine soil fills a bigger percentage of the macro-pores and thus increases the water absorption capacity the most.

5.3.4. Casting and curing

Prism samples
The samples for both the cement paste and the cement mortar are made in prism moulds with dimensions 40 mm x 40 mm x 160 mm. For the mixing of the cement paste a Hobart mixer is used. Mixing is done according to EN 196-1. The moulds are covered and are put in a curing room. The samples are taken out of the moulds after 3, 7 or 28 days of curing depending on the test that is conducted on the sample.

Cube samples
The samples for the first series of pervious concrete, the second series of pervious concrete and the pervious concrete with soil are all made in cubic moulds with dimensions 100 mm x 100 mm x 100 mm. To avoid the influence of moisture, all aggregates are soaked in water for at least 24 h, and then dried with a cloth to saturated surface dried (SSD) condition. The mixing is done by hand mixing. For the second series of pervious concrete, the cement paste is mixed with a Hobart mixer before adding the aggregates, since excellent mixing is needed to prevent clumping of the cement paste due to the use of the admixture Cugla Colloidaal 100. The samples are demoulded after 3 days and the cubes are placed in a curing room.

Table 5.12: Properties of the first batch of series for the pervious concrete samples

Series No.	Aggregate Type	Aggregate Fraction	WCR	Stabilizer
C1.1	Pumice Stone	8 / 11.2	0.6	Yes
C1.2	Pumice Stone	11.2 / 16	0.8	Yes
C1.3	Lava Stone	8 / 11.2	0.8	Yes
C1.4	Lava Stone	11.2 / 16	0.6	Yes

Table 5.13: Properties of the second batch of series for the pervious concrete samples

Series No.	Aggregate Type	Aggregate Fraction	WCR	Stabilizer	Admixture
C2.1	Lava Stone	8 / 16	0.4	No	Cugla Colloidaal 100
C2.2	Lava Stone	8 / 16	0.6	Yes	Cugla Colloidaal 100
C2.3	Lava Stone	8 / 16	0.8	Yes	Cugla Colloidaal 100

Table 5.14: Properties of the series for the pervious concrete samples with soil

Series No.	Aggregate Type	Aggregate Fraction	WCR	Stabilizer	Soil
C1.4_F	Lava Stone	11.2 / 16	0.6	Yes	Fine
C1.4_G	Lava Stone	11.2 / 16	0.6	Yes	Coarse

Adding soil mixture
For the series with soil, the samples are taken out of the curing room after at least 28 days of curing. The soil mixture is prepared by mixing soil, glue and water by hand in the proportions mentioned in paragraph 5.3.2. The sample is completely immersed in the soil mixture and the bucket with the sample and the soil mixture is put in a vacuum tank. Vacuum is applied for 10 minutes in which air is removed from the macro-pores. After 10 minutes, the vacuum is removed. Since the cube is immersed in the soil mixture, soil is sucked into the pores. An overview of the set up is given in Figure 5.4.

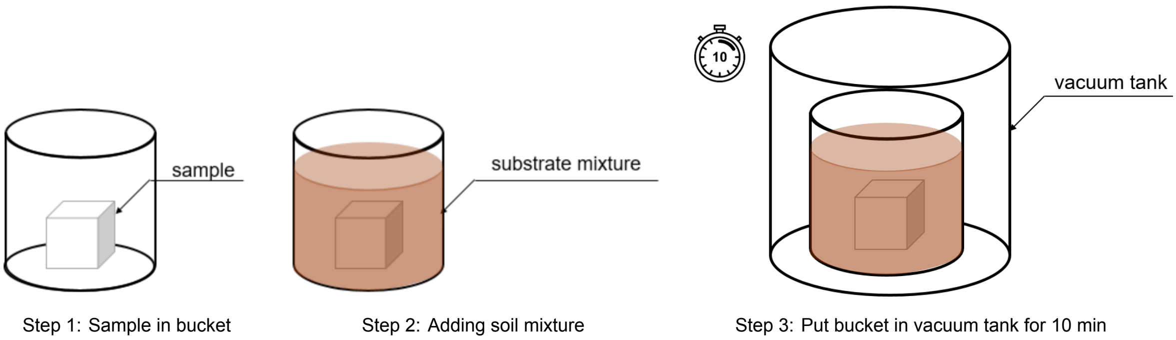


Figure 5.4: Overview of the set up for adding soil to the macro-pores

5.3.5. Testing procedures

Setting Time Determination
The setting time of the cement paste is determined, since it is expected that the addition of fibres and adjustment of the WCR effect the setting time. The setting of the cement paste is directly related to the setting time of pervious concrete and is thus extremely important as the pervious concrete is vulnerable especially in its early days. The determined setting times can be used to predict after which time the pervious concrete can be demoulded without damaging the pervious concrete. The setting time is determined conform NEN-EN 196-3:2016. The Vicat device is used according to the procedure in the standard.

Flexural strength testing
The flexural strength development is determined for the cement paste and the cement mortar by measuring the flexural strength after 3, 7 and 28 days. The flexural strength test is done conform NEN-EN 196-1:2016 with a 3-point bending test.

Compressive strength testing
The compressive strength development is determined for the cement paste, the cement mortar and the pervious concrete by measuring the compressive strength after 3, 7 and 28 days. The 3 day point is chosen instead of the 1 day point, as the pervious concrete cannot be demoulded after 1 day, since it is still too vulnerable at that moment. The compressive strength test on the cement paste and the mortar

are done conform NEN-EN 196-1:2016 on the halves of the 40 × 40 × 160 mm^3 prism after the flexural test. The compressive strength test on the pervious concrete is done conform NEN-EN 12390-3:2019 on the 100 x 100 x 100 mm^3 cubes.

Water absorption and evaporation
This test is performed for the cement paste samples, the pervious concrete samples and the pervious concrete samples with soil. The test method per sample type differs slightly and is discussed separately. Three samples of each series are tested in both phases. For the water absorption test the samples are immersed in water as Bakker and Roessink (1990) found no substantial difference in results for wetting by immersion and by spraying.

Test method for cement paste

The hardened cement paste prisms are put in the oven (100 ± 5 °C) and are dried until constant weight is reached. The dry weight of the specimens is recorded after which the specimens are immersed in water (20 ± 2 °C). The weight of the specimens is measured at predetermined times after immersion (5 min, 10 min, 30 min, 1h, 2h, 4h, 8h, 24h, 48h, 7d, 10d, 14d). Before it is weighed, the excess water is removed with a moist cloth. Afterwards the cumulative water absorption at all times is determined. The saturated prisms are put in in an environmental chamber with a constant temperature (20 ± 2 °C) and a constant humidity (55 ± 5 %). The weight of the specimens is measured at predetermined times (5 min, 10 min, 30 min, 1h, 2h, 4h, 8h, 24h, 48h, 7d, 10d, 14d). Afterwards the water evaporation at all times is determined.

Test method for pervious concrete

The pervious concrete cubes with and without soil are immersed in water after 26 days of curing in a moist room. After 28 days of curing the cubes are taken out of the water and are left to drain in the moist room. Excess water on the surface is removed with a moist cloth and the saturated weight of the cubes is recorded. By immersing the saturated surface dry cube in a measuring cup with a known quantity of water, the interconnected porosity can be determined by the volume difference. Afterwards, the cubes are put in an oven (100 ± 5 °C) until constant weight is reached. The dry weight is recorded after which the cubes are wrapped from 5 sides leaving one side open. The weight of the packed cubes is recorded and the cubes are immersed in a 10 mm thick layer of water, with the open side facing downwards. The weight of the specimens is measured at predetermined times (5 min, 10 min, 30 min, 1h, 2h, 4h, 8h, 24h, 72h, 7d, 10d, 14d). Before weighing excess water is removed with a moist cloth. Afterwards the water absorption at all times is determined. The cubes are put in an environmental chamber with a constant temperature (20 ± 2 °C) and a constant humidity (55 ± 5 %). The weight of the specimens is measured at predetermined times (5 min, 10 min, 30 min, 1h, 2h, 4h, 8h, 24h, 72h, 7d, 10d, 14d). Afterwards the water evaporation at all times is determined.

Pore structure by CT imaging
During a CT scan, a sample is placed between an X-ray source and a detector. The sample absorbs a certain amount of radiation, dependently on the material of the sample. In general, more radiation is absorbed when the density of the sample is higher. In this way the pore structure can be visualised as the density of air is much lower than the density of cementitious material.

The scanner used is a TESCAN CoreTOM CT scanner. In this scanner, the X-ray source, detector, and sample are fixed at a constant distance during the scan. The resolution is depended on the distance between the components. The sample rotates during the scan and at various angular positions 2D projections are made. These 2D projections are reconstructed into a 3D volume. More angular positions result in a more accurate image. The scans are made with the settings from Table 5.15.

Freeze-thaw resistance
The freeze-thaw durability of pervious concrete is significantly lower than that of conventional concrete. This makes the conventional testing methods for freeze-thaw resistance unsuitable. However, no standards exist for freeze-thaw tests on pervious concrete, thus the standard testing procedures should be adjusted to be able to do the tests on pervious concrete. The freeze-thaw resistance testing method

Table 5.15: Setting used for scanning of the samples with the TESCAN CoreTOM CT scanner. Different settings are used for P0.4 and P0.6 compared to P0.8.

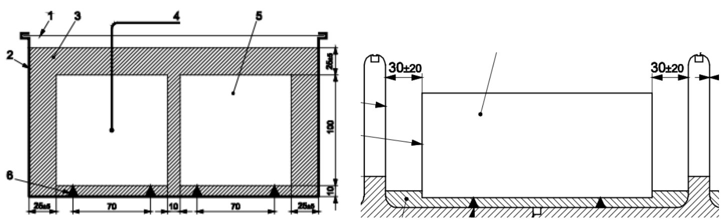
Sample	P0.4 & P0.6	P0.8
Voltage	140kV	140kV
Power	15W	15W
Voxel Size	3,7μm	4,5 μm
Exposure time	2100ms	1500ms
Projections	2160	1440
Average	1	1
Time/360°	1h 15m 35s	35m 59s

is based on CEN TS 12390-9. A combination of the alternative cube test method and the alternative CF/CDF test method is used with some alterations.

The alternative cube test method uses four 100 mm cube specimens per sample type which are subjected to 56 FT cycles completely immersed in 3% NaCl solution. After 7 ±1, 14 ±1, 28 ±1, 42 ±1 and 56 ±1 cycles, the mass loss of the detached pieces is determined. This is done by collecting the loosened pieces and drying those pieces in the oven to a constant mass. The CF/CDF test alternative method uses one half of a 150 mm cubes which is sealed from 4 sides and is put in a container with its test surface downwards. 3% NaCl solution is poured in the container to a height of 10 mm. The set up of both alternative test methods is visualised in Figure 5.5.

The alternated test method for this investigation uses 4 cubes of 100 mm, which are cured for at least 28 days. The cubes are wrapped from four sides, leaving the bottom and the top surface open. Two cubes are put in one container with the test surface down in 10 mm of 3% NaCl solution. The FT cycles are started after placing the containers in the FT machine. The following steps are carried out after 4, 6, 14, 18 and 28 FT cycles:

1. Take cube out of the container and gently shake 10 times up and down.
2. Collect the loosened material and dry in the oven.
3. Put the leftover of the cube back in the container. If needed cut the wrapping at the bottom to ensure the bottom surface is in contact with the 3% NaCl solution.
4. Pour in new freezing medium till a height of 10 mm.
5. Weigh the dried loosened material



(a) Cube test (b) CF/CDF test

Figure 5.5: Visualisation of the alternative test methods according to CEN TS 12390-9

6
Results

The results of the different phases are provided in this chapter. First the result of the tests on the cement paste and cement mortar samples are included. The results of the first series of pervious concrete are provided. Based on these results a second series of pervious concrete is tested and the results are included in the third paragraph. Finally the results of the pervious concrete samples with soil are provided.

6.1. Results of the paste and mortar mixtures

6.1.1. Setting time

Results

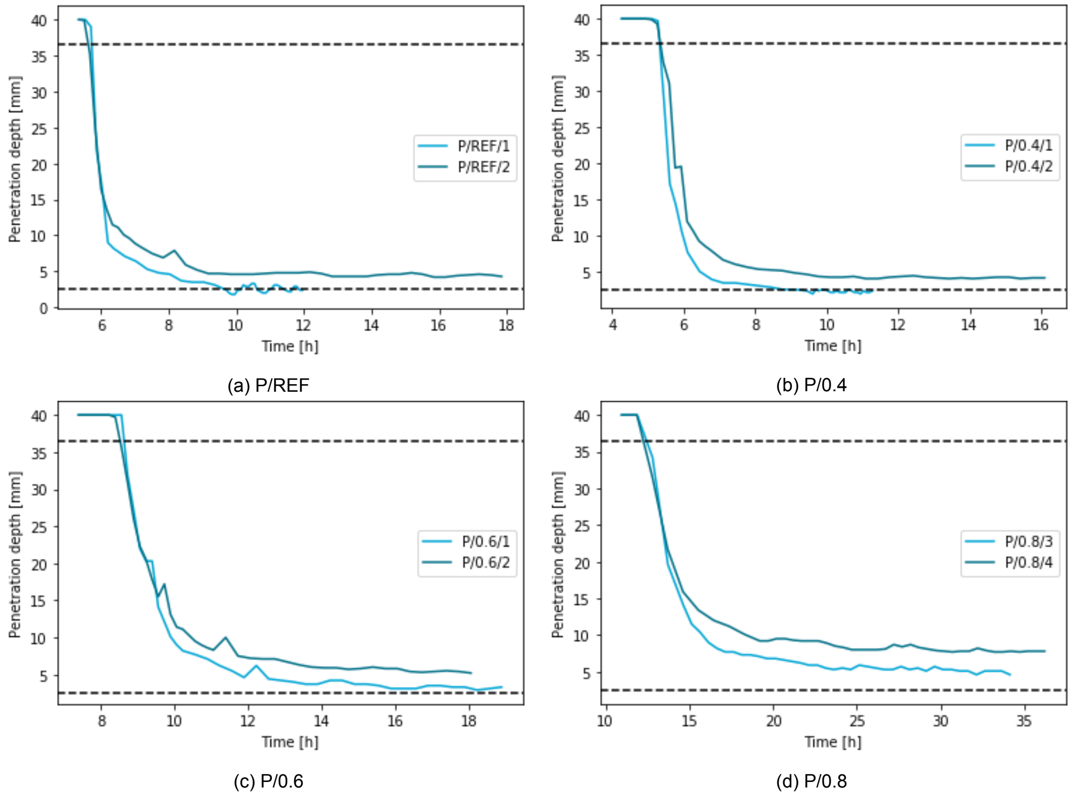
Using the measurements from the Vicat device, the initial and final setting time of the mixtures are determined. Figure 6.1 shows the measurements of the needle penetration depth over time. The time at which the penetration depth reaches 36.5 mm and 2.5 mm are the initial and final setting time respectively. As explained in Appendix A, there is a recurring error for one of the Vicat devices that is used. Therefore the penetration depth of 2.5 mm is not reached, although the curve of the graph shows that the final setting is reached within the testing time. Alternative penetration depths for the final setting for the samples tested with the Vicat device with the recurring error are determined according to Appendix A. Additionally, for the mixtures with WCRs 0.6 and 0.8, non of the measurements reach the penetration depth associated with the final setting. This is explained by the high shrinkage of the mixtures with a higher water content, which is visible in Figure 6.2. The high shrinkage lowers the upper surface, causing increased final penetration depth measurements. In Appendix A it is discussed which penetration depths are associated to the final setting of these mixtures. Table 6.1 shows the average initial and final setting time.

Table 6.1: Setting times determined with the Vicat device

	Initial setting time [h]		Final setting time [h]	
	AVG	STDV	AVG	STDV
P/REF	5.78	0.14	9.78	0.09
P/0.4	5.44	0.01	9.60	0.22
P/0.6	8.65	0.12	16.15	0.35
P/0.8	12.80	0.01	28.91	1.31

Interpretation

The results show that the initial and final setting time of the cement pastes decreases slightly due to the addition of micro-cellulose fibers, but taking into account the standard deviation no significant difference is identified. This indicates that micro-cellulose fibers are not a problem for the setting times. The increase of the setting times by increasing the WCR is in line with the expectations. The final



(a) P/REF

(b) P/0.4

(c) P/0.6

(d) P/0.8

Figure 6.1: Vicat measurements showing the needle penetration depth over time

Figure 6.2: Picture of P/0.8 sample after the setting time test

setting time is increased by a factor 3 with respect to the reference paste. The time before demoulding should be adapted based on this knowledge.

An additional finding is the fact that shrinkage in cement paste with a high WCR is extremely large due to evaporation of water from the mixture while setting. This property is not further investigated during this research, but it expected that the shrinkage of the cement paste does negatively effect the other properties in pervious concrete.

Conclusion
It is concluded that the final setting time is strongly increased due to increase of the WCR. For the pervious concrete samples a demoulding time of 3 days is chosen instead of 1 day, as the final setting time is increased by a factor of 3.

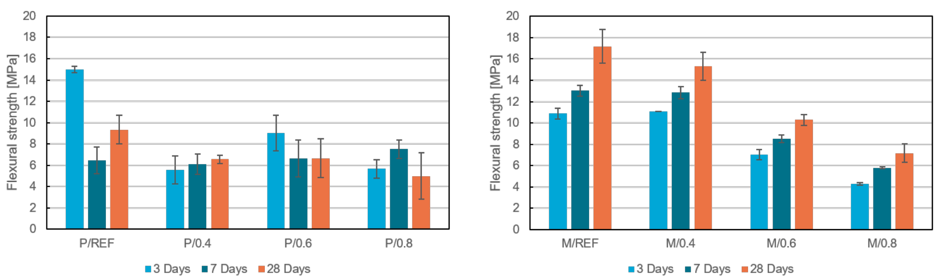
6.1.2. Flexural strength

Results
The results of the flexural strength of the four paste mixtures after 3, 7 and 28 days of curing are provided in Figure 6.3a. Figure 6.3b shows the flexural strength results of the associated mortar mixtures after 3, 7 and 28 days of curing of each mix design. The error bars are the standard deviations based on 3 replicates. The reference mix designs (P/REF and M/REF) are compared with the 0.4 mix designs (P/0.4 and M/0.4) to determine the effect of the micro-cellulose fibers on the flexural strength properties. The mix designs including fibers with WCRs of 0.4 (P/0.4 and M/0.4), 0.6 (P/0.6 and M/0.6) and 0.8 (P/0.8 and M/0.8) are compared to determine the effect of changing the WCR.

Interpretation
In general the results of the flexural strength development of the mortar samples shows a more consistent trend with a lower standard deviation compared to the results of the paste samples. This result explains why cement mortar is more commonly used for compressive and flexural strength testing in research papers and why cement producers base their strength values on mortar samples.

Due to the extremely high standard deviation of the results of the paste samples, it is difficult to make any statements about those results. Striking is the extremely high flexural strength at 3-day curing age with a low standard deviation for the reference mix design. This trend is not seen for the flexural strength of the cement mortar reference mix design. It can possibly be explained by the fact that cracks in cement paste samples are clearly reflected in the flexural strength (Klun et al., 2021). The lower WCR of the reference mixture, causes slower crack formation compared to the higher WCRs, resulting in higher early age flexural strength. Due to crack formation the flexural strength is reduced after a curing age of 7 days. This trend is not visible for the mortar samples, since cement mortar has better fracture properties than cement paste (Zhu and Xu, 2007). Despite the high standard deviation it is observed that the flexural strength is roughly around 6 MPa, which is a logical value when considering that the flexural strength is approximately 10 to 20% of the compressive strength.

As mentioned before, the flexural strength of the mortar samples has lower standard deviations. The flexural strength obtained with the mortar samples is expected to be higher due to the incorporation of fine aggregates (Klun et al., 2021), but due to the inconsistent results of the paste samples, this assumption cannot be confirmed by the results. When comparing the M/REF and M/0.4 no significant difference is seen in the flexural strength, implicating that the addition of micro-cellulose fibers does not effect the flexural strength. By comparing the flexural strength development of M/0.4, M/0.6 and M/0.8, it is concluded that a higher WCR decreases the flexural strength development.



(a) Cement paste (b) Cement mortar

Figure 6.3: Flexural strength development

Conclusion
As no sand is included in the mix designs for pervious concrete, the results of the cement paste samples are more interesting for this investigation. As the flexural strength is roughly around 6 MPa for all mix designs, they all seem suitable for implementation in the pervious concrete based on the cement paste results. However, due to the high standard deviations in the paste results, the results of the mortar samples should also be considered. Those results show a reduction of approximately 58% of the M/0.8 mix design compared to the M/REF mix design, which might be a problem for the the production of pervious concrete. Nevertheless, due to the difference between the paste and the mortar and the unknown relation between the flexural strength of the paste and mortar to the strength properties of the pervious concrete, non of the WCRs are excluded for implementation in the pervious concrete based on the flexural strength results.

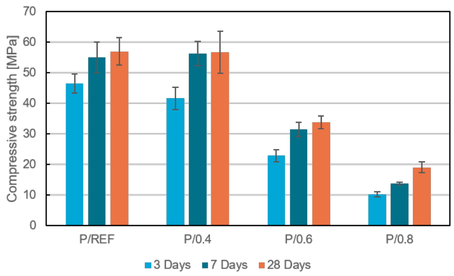
6.1.3. Compressive strength

Results
The results of the compressive strength of the four paste mixtures after 3, 7 and 28 days of curing are provided in Figure 6.4a. Figure 6.4b shows the compressive strength results of the associated mortar mixtures after 3, 7 and 28 days of curing of each mix design. The error bars are the standard deviations based on 6 replicates. The reference mix designs (P/REF and M/REF) are compared with the 0.4 mix designs (P/0.4 and M/0.4) to determine the effect of the micro-cellulose fibers on the compressive strength properties. The set of the 0.4 (P/0.4 and M/0.4), 0.6 (P/0.6 and M/0.6) and 0.8 (P/0.8 and M/0.8) mix designs are compared to determine the effect of changing the WCR.

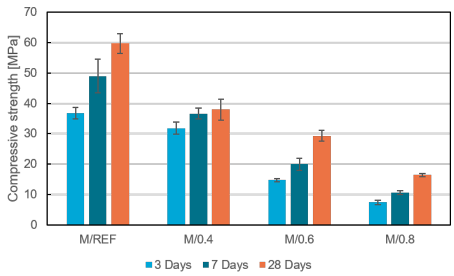
Interpretation
The trends of the compressive strength development of the paste samples are more consistent than they are for the flexural strength development. The compressive strength results of both the mortar and the paste can thus be used to make statements.

When comparing the P/REF and P/0.4 no significant difference is seen in the compressive strength, implicating that the addition of micro-cellulose fibers does not effect the compressive strength. However, the results of M/REF and M/0.4 contradict this finding as the compressive strength development of M/0.4 is lower than the strength development of M/REF. Furthermore, the strength development in the period of 3 to 28 days of curing is extremely low for M/0.4 in contrast to the compressive strength development of the other two mix designs including micro-cellulose fibers. No explanation is found for this absence of significant strength increase from a curing age of 3 to 28 days. By comparing the compressive strength development of P/0.4, P/0.6 and P/0.8 it is concluded that a higher WCR decreases the compressive strength development. The same conclusion is drawn from the results for M/0.4, M/0.6 and M/0.8.

For each test only a limited amount of specimens is used, leading to relatively high standard deviation. The execution of the mixing procedure could have had an influence on the properties of the mixtures. Especially for the mixtures with limited workability (P/0.4 and M/0.4), small deviations in casting could have affected the material properties.



(a) Cement paste



(b) Cement mortar

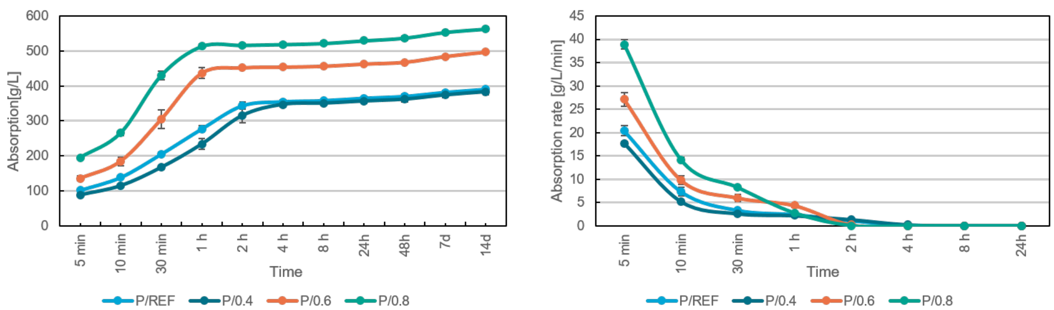
Figure 6.4: Compressive strength development

Conclusion
As no sand is included in the mix designs for pervious concrete, the results of the cement paste samples are more interesting for this investigation, but the mechanical and physical properties of the cement provided by the supplier are based on tests on mortar samples. When comparing the results to the values provided by the supplier, it is thus better to look at the results from the mortar samples. The cement type is CEM III/B 42.5 N, which has a minimum compressive strength of 42.5 MPa after 28 days of curing. This is easily obtained by the reference mix design, but it is not obtained for the other mix designs. However, when considering a lower minimum compressive strength of only 32.5 MPa, which is associated to the conventional cement class 32.5, more mix designs fulfil the requirement. A 32.5 MPa strength is obtained by M/REF and M/0.4 and is almost obtained by M/0.6. Only for mix design M/0.8 the compressive strength is significantly below that value. This would indicate that it is better to exclude the M/0.8 mix design from further investigation. However, as the relation between the compressive strength of the cement mortar and the compressive strength of the pervious concrete is unknown, the WCR of 0.8 is not excluded in the pervious concrete mix design if the water absorption test results of P/0.8 are very promising.

6.1.4. Water absorption

Results
The cumulative water absorption of the four paste mixtures after 28 days of curing is provided in Figure 6.5a. From the cumulative water absorption, the water absorption rate is determined by dividing the difference in water absorption per time frame by the time between the measurements. The results are included in Figure 6.5b. The error bars are the standard deviations based on 3 replicates. The reference mix design (P/REF) is compared to the 0.4 mix design (P/0.4) to determine the effect of the micro-cellulose fibers on the water absorption properties. The sets of the P/0.4, P/0.6 and P/0.8 mix designs are compared to determine the effect of changing the WCR.

Interpretation
Most of the error bars are narrow, meaning that the standard deviation of the measurements is low, which implicates that the results are reliable. Four lines can clearly be distinguished in the graph, but the graphs from P/REF and P/0.4 are similar after 4 hours of immersion as this is the point that both mix design have approximately reached full saturation conditions. Before that moment the P/REF graph is higher, meaning that the water absorption is a bit faster without the incorporation of micro-cellulose fibers, but the eventual saturation reaches the same value. This finding is confirmed by the water absorption rate graphs. The water absorption rate in the first 5 minutes by including micro-cellulose fibers is 13.3% lower compared to the reference mix design. The graphs of P/0.6 and P/0.8 show a similar trend, reaching fully saturated conditions after approximately 1 hour. The P/0.8 graph is starting a bit higher, meaning that the water absorption rate of the mixture with a higher WCR is especially higher in the first 5 minutes. After that the water absorption rate of the mixtures with WCR 0.6 and 0.8 becomes more identical, which is also confirmed by the water absorption rate graph. The water absorption rate in the first 5 minutes for the mix designs with a WCR of 0.6 and 0.8 is respectively 53.5%



(a) Cumulative water absorption

(b) Water absorption rate

Figure 6.5: Water absorption characteristics of cement paste samples immersed in water

and 120.2% higher compared to the mix design with a WCR of 0.4. All those mix designs contained micro-cellulose fibers.

The maximum water absorption capacity is not important, since the volume of the cement paste in the pervious concrete is low, meaning that water storage in the cement layer is an extremely small part of the total water absorption of pervious concrete. Optimization of this small share is thus not beneficial. However, the water permeability is important for the eventual pervious concrete mix design, as passage is crucial for the eventual water absorption in the coarse aggregate. The focus is thus on the water absorption (rate) in the first hours of the investigation, which is related to the water permeability of the cement paste. The addition of micro-cellulose fibers decreases the initial water absorption rate, which is explained by the blockage of pores by the fibers. This result in a longer time needed to reach full saturation. The level of full saturation is not effected by the micro-cellulose fibers as the volume of the fibers is small, so this does not effect the interconnected pore volume. Increasing the WCR increases the initial water absorption rate, which can be explained by the increased porosity of the hardened cement pastes with higher WCRs.

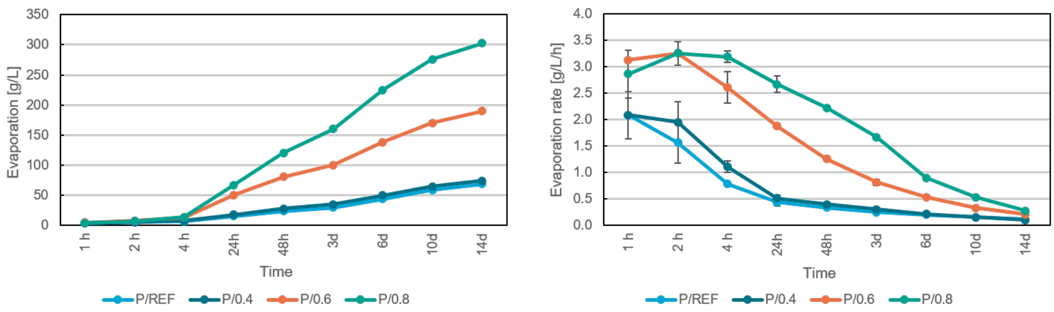
As a result of drying the samples in the oven at 100 °C before testing, cracks occur in the hardened cement paste. These cracks, might contribute to the water absorption and thus influence the results. Therefore the water absorption results should be verified by CT scans, to conclude if differences on micro-scale are visible. It would have been better to test smaller samples for the cement paste, as drying at lower temperatures would have been possible, which causes less crack formation.

Conclusion
Although the addition of micro-cellulose fibers reduces the initial water absorption rate, the water absorption rate of the mix designs with a WCR of 0.6 including fibers is higher than the reference mix design with a WCR of 0.4 without fibers. This means that increasing the WCR by 0.2 has more effect than including fibers. This indicates that increasing the WCR is an appropriate method for improving the initial water absorption rate even though the addition of micro-cellulose fibers is needed in case of a higher WCR. As the difference between the water absorption rate in the first 5 minutes between P/REF and P/0.6 is quite small compared to the difference between P/0.8 and P/0.6, inclusion of the 0.8 level for the WCR in the pervious concrete mix designs is recommended to be able to clearly indicate the impact of adjusting the WCR on the trendlines. As the workability of the cement paste with a WCR of 0.4 including fibers is not appropriate and adjusting another parameter by leaving out the fibers is not desired, the WCRs used in the first series of the pervious concrete mix designs are 0.6 and 0.8.

6.1.5. Water evaporation

Results
The cumulative water evaporation at constant temperature (20 ± 2 °C) and constant humidity (55 ± 5 %) of the four paste mixtures is provided in Figure 6.6a. At the start of the test, the samples are fully saturated after immersion in water for 14 days. From the cumulative water evaporation the water evaporation rate is determined by dividing the difference in water evaporation per time frame by the time between the measurements. The results are included in Figure 6.6b. The error bars are the standard deviations based on 3 replicates. The reference mix design (P/REF) is compared to the 0.4 mix design (P/0.4) to determine the effect of the micro-cellulose fibers on the water evaporation properties. The sets of the P/0.4, P/0.6 and P/0.8 mix designs are compared to determine the effect of changing the WCR.

The error bars are narrow and almost not visible in the graph of the cumulative water evaporation. For the measurements after 4 hours this means that the standard deviation of the measurements is low. However, the early measurements up till 4 hours are close to zero. The standard deviations of those measurements are relatively high despite the fact that they are not visible in the left graph, which complies with the wide error bars in the water evaporation rate graph up till the 4 hour measurement. Some earlier measurements are done before the 1 hour mark, but as this would lead to a long flat beginning of the evaporation graph and even wider standard deviations in the evaporation rate graph, the first 3 measurements points at 5, 10 and 30 minutes are not included in the graphs.



(a) Cumulative water evaporation

(b) Water evaporation rate

Figure 6.6: Water evaporation characteristics of cement paste samples in climate chamber (T = 20 ± 2 °C, RH = 55 ± 5 %)

Interpretation

Again the focus is on the water evaporation rate, as the cement is only regarded as a passage layer and not as a material for water accumulation.

Although the water absorption rate and water evaporation rate are closely related, the inclusion of micro-cellulose fibers does not seem to impact the water evaporation (rate) as it did with the water absorption (rate). Only three lines can namely be distinguished in Figure 6.5a as the graphs of P/REF and P/0.4 are very similar. The graphs of the evaporation rate show some difference from the first to the fourth hour, but due to the high standard deviations, this is not regarded as a significant difference. The lack of difference between the mix design with and without fibers for evaporation can partly be explained by the inaccuracy of the measurements in the first 4 hours. Precisely in that time frame the difference in water absorption rate is observed, so that would also be the time frame where the difference in water evaporation rate would have appeared. Additionally, the conditions for evaporation are less extreme than the conditions for the water absorption test. For the water absorption test the hardened paste samples are completely immersed in water. Blockage of pores by fibers in that case restricts the water absorption as the rate is extremely high and all pores are contributing. The water evaporation test takes place at less extreme conditions. Therefore the water evaporation rate is lower and the effect of blockage of pores does not appear in the results.

As expected, increasing the WCR increases the water evaporation rates of the mix designs with higher WCRs are higher, which is in accordance with the water absorption rates. The water evaporation rates in the period from 24 to 48 hours for the mix designs with a WCR of 0.6 and 0.8 is respectively 215.0% and 456.5% higher compared to the mix design with a WCR of 0.4. All those mix designs contained micro-cellulose fibers. This can be explained by the increased porosity of the hardened cement pastes with higher WCRs. In addition, the initial moisture content of the samples with a higher WCR are also higher, meaning that there is more water absorbed by the samples at the start of the evaporation test. Combining the knowledge on the porosity and moisture content explains the fact that the differences in water evaporation are more striking than the differences that are seen for the water absorption.

Conclusion

Since the water absorption rate is directly related to the water evaporation rate, it is difficult to optimize both properties. Maximizing the water absorption rate is the primary goal. The fact that the water evaporation is high for higher WCRs is expected and is not directly a problem for the pervious concrete mix design. However, it might be needed to consider extra measurements to reduce the evaporation in the pervious concrete quay wall panel. If this is needed should be determined by testing the water absorption and evaporation properties of the pervious concrete mix designs. The recommendations for the levels for varying the WCR parameter provided in the conclusion of the water absorption test can be utilized.

6.1.6. CT scan

Results

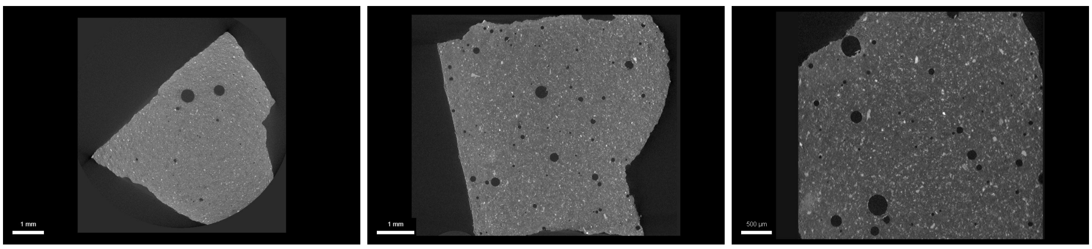
A CT scan is made to visualize the pore structure of the three paste mixtures containing micro-cellulose fibers. A 2D image of the CT scan is provided in Figure 6.7. The scale bar indicates the dimensions of the scan. Pores up till a diameter of approximately 4 μm are visible on this scan. This means that only macro-pores (>10 micrometer) are visible on the scan. The capillary pores (0.01 - 0.1 μm), submicron large pores (0.1 - 1 μm) and micron large pores (1 - 10 μm) have more influence on the water transport properties than the macro-pores, which are visible on the CT images. The smaller scales are not visible, but since the larger pores to a lesser degree also influence water transport properties the interpretation of the images is done based on that scale. No CT scan is made of the mix design without micro-cellulose fibers, since the particle diameter of the fibers is in the order of 0.1μm and can thus not be seen in a CT scan on this scale. Making a scan for the reference mix design will result in the same image as for mix design P/0.4.

Interpretation
In the image of the CT scan of the mix design with a WCR of 0.4, significantly less pores are seen. Some big pores appear, which is explained by the fact that the samples are not vibrated during casting. Therefore, air voids are enclosed in the samples, which is visible as a big pore. The mix designs with a WCR of 0.6 and 0.8 contain more smaller visible pores than the mix design with a WCR of 0.4. However, no clear distinction is seen between P/0.6 and P/0.8. This is not in accordance with the water absorption of those samples which would suggest that P/0.8 has more pores. Possibly this could be explained by the fact that capillary pores are not visible on the CT images. As those have the most impact on the water transport properties and it is expected that P/0.8 has more capillary pores than P/0.6, this could explain that no difference is seen on the CT scan, but the water absorption results did show a difference. Additional research (for example Mercury Intrusion Porosimetry) is needed to confirm this. Another possibility is that the crack formation due to drying of the samples before testing effects the water absorption of the cement paste samples and more cracks are formed in the samples with a WCR of 0.8.

Conclusion
The CT scans are made to validate the results of the water absorption test. However, as the scale of the CT scans is not appropriate to distinguish the capillary pores, it is not possible to validate the water absorption test results. It is concluded that all paste mixtures include some big pores, which can be explained by the lack of vibration when the samples are casted. It is visible that the mix design with a WCR of 0.4 contains less small pores than the mix designs with higher WCRs.

6.1.7. Conclusion paste and mortar phase

The flexural and compressive strength of the cement mortar samples is reduced when the WCR is increased. The 28-day compressive strength of the reference mixture, the mixture with a WCR equal to 0.6 and the mixture with a WCR equal to 0.8 are 59.6 MPa, 29.4 MPa and 16.5 MPa, respectively. The cement mortar samples with increased WCR thus do not reach the compressive strength requirement of CEM III/B 42.5 N, but the minimum compressive strength of the pervious concrete is only 6 MPa. As the effect of the strength of the cement on the strength properties of the pervious concrete is unknown, non of the WCRs are excluded for the pervious concrete mix designs based on the strength testing in this phase. The water absorption results show that increasing the WCR is an appropriate method to increase the initial water absorption rate, which is assumed important for the water absorption rate of pervious concrete. As the difference between the initial water absorption rate between P/REF and P/0.6 is small, a WCR level of 0.8 is included in the mix designs of the first series of pervious concrete



(a) P/0.4 (b) P/0.6 (c) P/0.8

Figure 6.7: CT scans of the cement paste samples

to clearly indicate the impact of adjusting the WCR on the trendlines. For the second level a WCR of 0.6 is chosen, since the workability of the cement paste with a WCR of 0.4 with the inclusion of fibers is inappropriate. A demoulding time of 3 days is chosen for the pervious concrete samples as the final setting time increased due to the use of higher WCRs.

6.2. Results of the 1st series of pervious concrete

6.2.1. Important remark

The dry particle density and the water absorption of the aggregate types are used to adjust the original mix design from Holcim Group Lyon to the mix designs used in the first series of pervious concrete. The pyknometer test is performed after casting the samples for the first series of pervious concrete. Therefore, assumption had to be made for adjusting the original mix design. These assumptions are explicitly explained in Appendix B. Since the assumptions for the dry particle density and the water absorption of pumice stone are inaccurate, one more parameter is unknowingly varied in the mix designs. The values for the density and the water absorption obtained with the pyknometer test are lower than the estimated density and water absorption as is seen in Table 6.2. The consequence of this is that mix design C1.1 and C1.2 contain only 66% of the cement paste volume of the other two mix designs, resulting in a thinner cement paste layer coating the pumice stone aggregates. The trends that are seen for the aggregate type parameter are thus also the result of the different aggregate-to-cement paste volume ratio (ACR). More information on the effect of the false assumptions can be found in Appendix B.

Table 6.2: The estimated and tested values for the dry particle density and the 24h water absorption. Note that the estimated values for pumice stone do not corresponds to the values found with the pyknometer test. Due to the over estimations, the ACR is unknowingly varied in the mix designs of the first series.

	Lava stone		Pumice stone	
	Estimated	Tested	Estimated	Tested
Dry particle density [kg/m^3]	2580	2574.2	1287	870.4
24h Water absorption [%]	6.5	6.6	68	63

6.2.2. Porosity

Results

Macro-pores are an important element of pervious concrete. To determine the influence of this element on the other properties, the volume of the macro-pores is determined. Only the volume of the interconnected macro-pores is measured in this test. For the four mix designs of the first series the void ratios are provided in Figure 6.8. The error bars are the standard deviations based on 3 replicates.

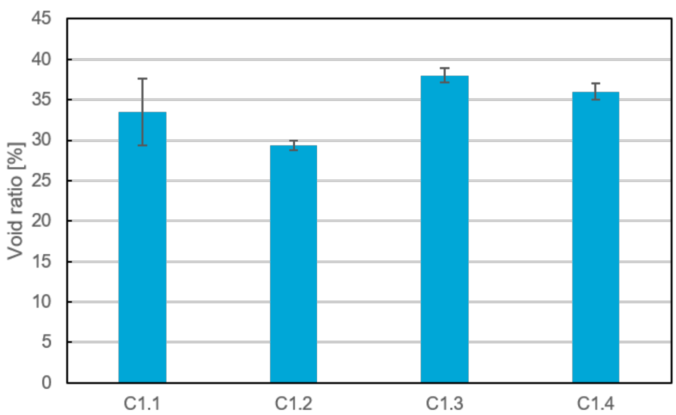


Figure 6.8: Void ratio of the first series of pervious concrete

Interpretation
It is clear that the void ratio of all tested mix design is above the minimum void ratio of 18%. The values per mix design diverge, which should be taken into account when evaluating the other tested properties. It accidentally causes the change of an extra parameter. The void ratio of mix designs C1.3 and C1.4 are above 35%, which is probably beneficial for the vegetation, but has negative consequences for the other properties. The standard deviation of the first mix design is very high. This could be due to the hand compaction method that is used leading to heterogeneous samples. It would however not explain why this high standard deviation is not seen in the other mix designs and would suggest that it is mere coincidence that the other standard deviations are low. The effect of the aggregate type on the void ratio is explained by the particle form of the aggregates. The shape of the aggregates effects the porosity as discussed in paragraph 4.2.4. The pervious concrete sample made with lava stone aggregates is expected to have a higher void content than a sample made with the the same fraction of pumice stone aggregates. However, due to the high standard deviation of the results of mix design C1.1 it is not possible to accurately state the effect of the aggregate type on the porosity.

Conclusion
As the void ratio for most mix designs is far above the minimum interconnected void ratio of 18%, it is possible to make mix designs with a lower void ratio. This should be done if the mix designs of this first series do not behave sufficient for compressive strength and freeze-thaw durability. Reducing the void ratio can be done by increasing the cement paste volume. The compaction method is not changed as the standard deviation of most mix designs is low, suggesting that the samples are not too heterogeneous.

6.2.3. Compressive strength

Results
The results of compressive strength development of the 4 pervious concrete mixtures after 3, 7 and 28 days of curing are provided in Figure 6.9. As multiple parameters are varied according to the Taguchi method, a Taguchi analysis is performed to determine the effect of the parameters. Figure 6.10 shows the trend of each mix design parameter (Aggregate Type, Aggregate Fraction and WCR) on the development of compressive strength using the signal-to-noise values. The influence of each mix design parameter on the compressive strength at different curing ages is shown in Figure 6.11. The influence of the 3 mix design parameters combined adds up to 100%.

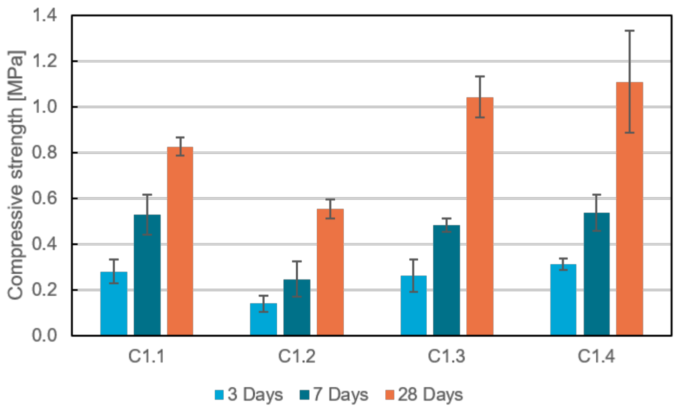
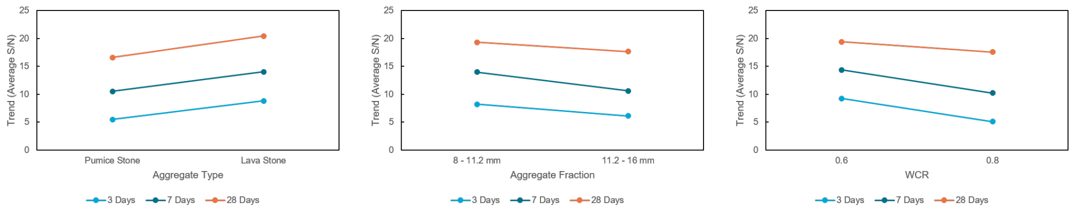


Figure 6.9: Compressive strength development of pervious concrete samples under different curing ages

Interpretation
Non of the mix design reach the compressive strength requirement of 6 MPa after 28 days of curing. The highest compressive strength is obtained for mix design C1.3 and C1.4, with a strength of approximately 1 MPa. With the higher void-ratio of both of these mixtures, a lower compressive strength is expected if non of the other parameters is varied. This indicates that the influence of the parameters is probably underestimated in the Taguchi analysis, since the void ratio is not taken into account for



(a) Influence aggregate type on the compressive strength

(b) Influence aggregate fraction on the compressive strength

(c) Influence WCR on the compressive strength

Figure 6.10: Taguchi trends for compressive strength development at different curing ages

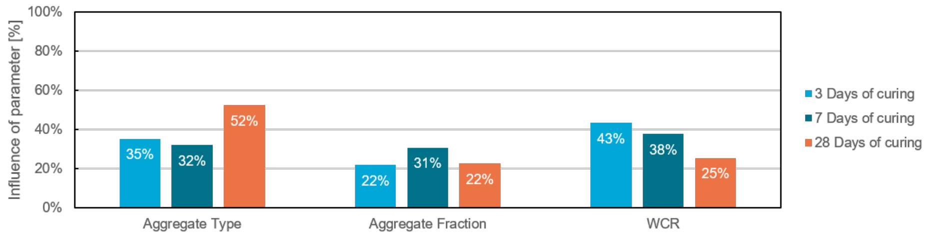


Figure 6.11: Influence of each mix design parameter on the compressive strength development at different curing durations

this analysis. C1.3 and C1.4 are the mix designs with the lava stone as coarse aggregate material. This is in accordance with the Taguchi trendline for the effect of the aggregate type on the compressive strength at 28 days, which influence is equal to 52%. It meets the expectations, since the lava stone has a higher density and a higher CBR value than pumice stone, which results in a higher strength aggregate material. Furthermore, the particle form and roughness of the lava stone aggregate enhance the compressive strength properties compared to the pumice stone aggregate as is discussed in paragraph 4.2.1.

This trend is not seen for 3 and 7 days of curing. After 3 days of curing, the parameter with the most influence is the WCR with 43%. This is explained by the failure pattern observed in the compressive testing at 3 days of curing which is shown in Figure 6.12 for mix design C1.2 and C1.4. All mix design failed due to failure of the bond between the aggregates and no failure of the aggregates is observed. This is concluded from the loosened pieces, which are clearly visible in both Figure 6.12a and Figure 6.12b. Since the WCR is influencing the strength of the cement paste it is logical that this parameter is most governing at a low age where the strength of the cement is governing for the strength of the pervious concrete.

At 28 days of curing, the failure patterns are still quite similar to the failure patterns at 3 days of curing as is seen in Figure 6.13, but it is observed that some of the failure occurs due to failure of the aggregate itself as is shown in Figure 6.14. However, the high influence of the aggregate type parameter on the 28-day compressive strength cannot solely be contributed to the difference in strength between the two aggregate types. As explained in paragraph 6.2.1 and in Appendix B the properties of pumice stone used for the alteration of the mix design from lava stone to pumice stone, is based on assumptions of the density and the 24h water absorption of the pumice stone. Testing has shown that those assumptions deviate from the actual values, which means that less cement paste is used in the samples with pumice stone compared to the samples with lava stone. In the mix designs with pumice stone the cement paste volume is only 66% of the volume that should have been used for fair comparison. The influence of the aggregate type parameter is therefore partly attributed to the fact that less cement paste volume results in lower bonding strength between the aggregates.

Conclusion

As the 28-day strength values of all mix designs are far below the requirement, non of the mix design are suitable for implementation as finishing layer of a quay wall. A second series of mix design is developed to improve the compressive strength. As the failure patterns for the compressive strength testing at

(a) C1.2 (b) C1.4

Figure 6.12: Failure pattern of compressive strength testing at 3 day curing age

(a) C1.2 (b) C1.4

Figure 6.13: Failure pattern of compressive strength testing at 28-day curing age

(a) Pumice stone aggregate (b) Lava stone aggregate

Figure 6.14: Failure of the aggregate

both 3 and 28 days of curing show that the failure of the pervious concrete mix design is mostly due to failure of the bond, the cement paste bonding is strengthened in the second series of the pervious concrete, to increase the compressive strength. Strengthening of the cement paste can be done by increasing the cement paste volume resulting in a thicker cement paste layer coating the aggregates or by reducing the WCR. As the strength of the tested mix design has to be improved by a factor of 6, it is concluded that increasing the cement paste volume is essential to improve the compressive strength properties. Combining this with a decrease in WCR will hopefully lead to a mix design that suffices for the compressive strength.

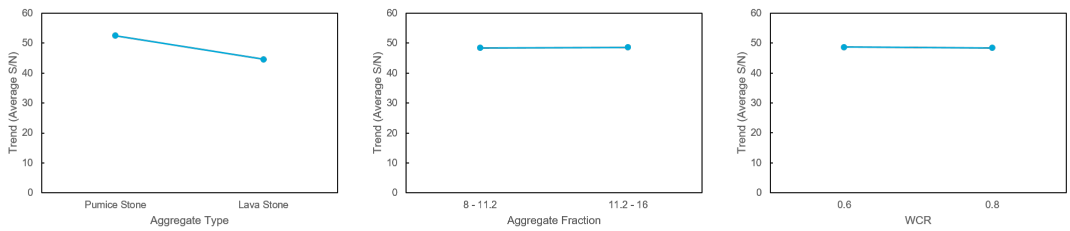
6.2.4. Water absorption

Results
The maximum water absorption capacity of the 4 pervious concrete mixtures is determined by complete immersion in water and is provided in Table 6.3. Figure 6.15 shows the trend of each mix design parameter (Aggregate Type, Aggregate Fraction and WCR) on the maximum water absorption capacity using the signal-to-noise values.

The cumulative water absorption of the four mixtures when one side is immersed in a small layer of water is provided in Figure 6.16a. From the cumulative water absorption the water absorption rate is determined by dividing the difference in water absorption per time frame by the time between the measurements. The results are included in Figure 6.16b. The error bars are the standard deviations based on 3 replicates. The maximum water absorption capacity is determined with a low standard deviation and the results are thus reliable. Taguchi trendlines are made for the water absorption rate at different time frames and can be found in Figure 6.17. The influence of each mix design parameter on the water absorption rate at different time frames is shown in Figure 6.18. The influence of the 3 mix design parameters combined adds up to 100%.

Table 6.3: Maximum water absorption capacity of the mix design of the first series of pervious concrete. Standard deviation is based on three replicates per mix design.

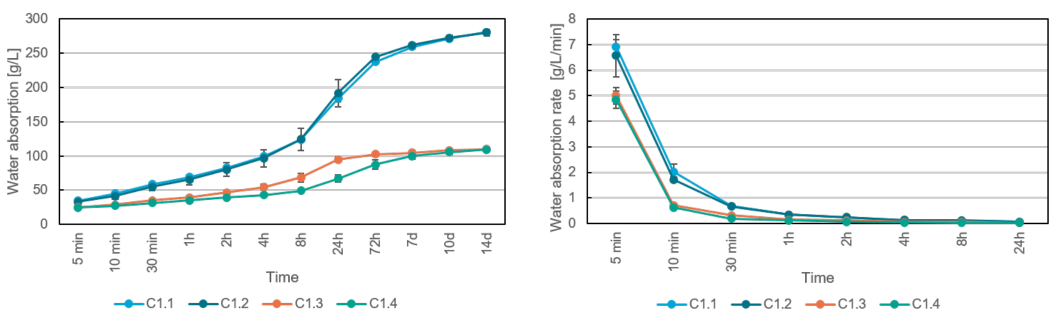
	Water absorption capacity [g/L]	Standard deviation [g/L]
C1.1	421.8	7.0
C1.2	418.7	5.4
C1.3	165.2	3.3
C1.4	174.0	6.9



(a) Influence of aggregate type (b) Influence of aggregate fraction (c) Influence of WCR

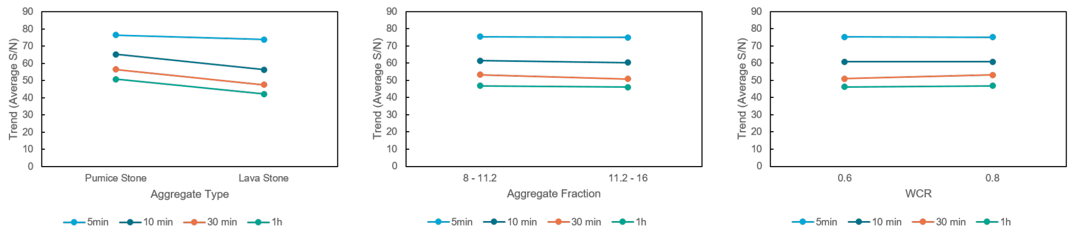
Figure 6.15: Taguchi trends for the maximum water absorption capacity

Interpretation
The Taguchi trendlines in Figure 6.15 show that the maximum water absorption capacity is mostly influenced by the aggregate type. This mix design parameter has an influence of 94.7%. This is



(a) Cumulative water absorption (b) Water absorption rate

Figure 6.16: Water absorption characteristics of the first series of pervious concrete samples immersed in a small layer of water



(a) Influence of aggregate type (b) Influence of aggregate fraction (c) Influence of WCR

Figure 6.17: Taguchi trends for the water absorption rate

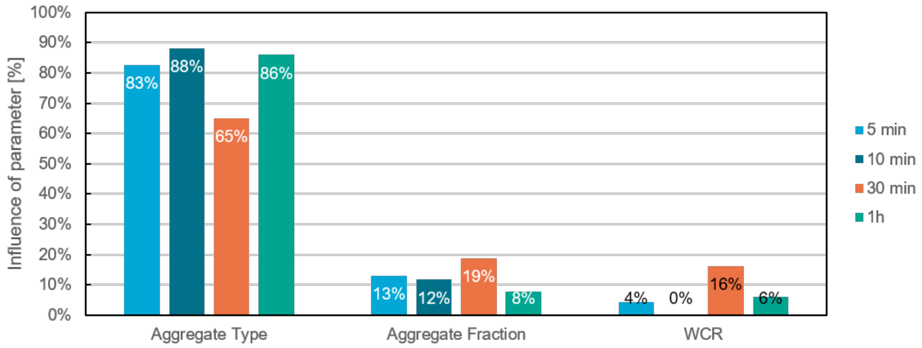


Figure 6.18: Influence of each mix design parameter on the water absorption rate at different time frames

in accordance with the large difference that is found for the water absorption of the raw aggregate material. The raw pumice stone aggregate absorbed 3.6 times more water per volume of aggregate than the raw lava stone aggregate. The water absorption of the pervious concrete made with pumice stone aggregate is approximately 2.5 times the value of the water absorption of pervious concrete made with lava stone aggregate. The difference is thus a bit lower than the difference for the raw materials, which is explained by the fact that a part of the water absorption in pervious concrete is water adhering to cement paste layer in the macro-pores inside the cube, which could not be removed. As this is contributing in both the mixture with pumice stone and with lava stone, the difference due to water absorption of the aggregate itself is lower.

Before testing it is believed that the cement layer is blocking the water transport to the aggregate. However, since the influence of the WCR parameter is only 3%, this proves that the cement layer in these mix design is not restricting the maximum water absorption. As the water absorption rate at all times is also hardly influenced by the WCR, the cement layer is proved to play no role in the absorption characteristics of these mix designs. However, from the compressive strength testing it became clear that the mix design are by far not reaching the minimum strength demand and it is concluded that the volume of cement paste should be increased in the second series. A thicker cement coating around the aggregates, may cause a higher influence of the WCR ratio on the water absorption characteristics.

The influence of the aggregate fraction on the water absorption characteristics is insignificant, which corresponds to the expectations for this parameter, especially since the range chosen for this fraction is really small.

Conclusion

Using an aggregate material with a higher water absorption promoted the maximum water absorption capacity and the water absorption rate considerably. However, if an aggregate material with high water absorption can be used in pervious mix designs should be determined with freeze-thaw experiments. Increased water absorption can namely be a problem for freeze-thaw durability. Additionally, more research is needed to conclude if water absorption of the aggregate is also possible when the cement coating thickness is increased. When those two things are proven to not be a problem, the use of a highly water absorbing aggregate is recommended for improving water retention in pervious concrete.

6.2.5. Water evaporation

Results

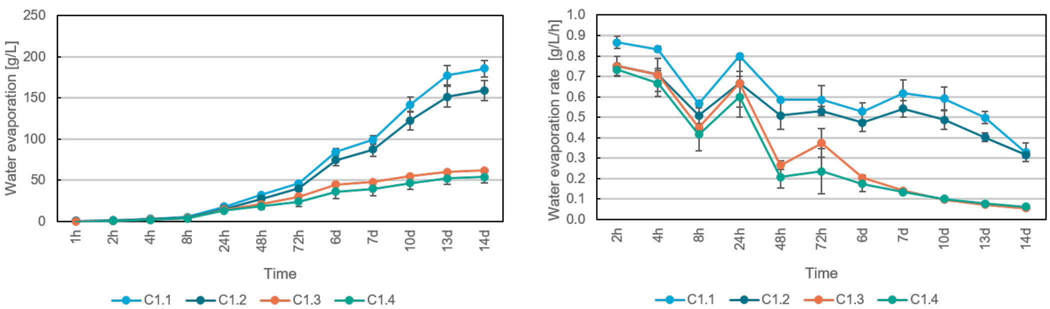
Figure 6.19 shows the cumulative water evaporation and the water evaporation rate at constant temperature (20 ± 2 °C) and constant humidity (55 ± 5 %). The early measurements up till 8 hours are close to zero, but have relatively high standard deviations. Some earlier measurements are done before the 2 hour mark, but as this would lead to a long flat beginning of the evaporation graph and higher standard deviations, the first 4 measurements points at 5, 10, 30 and 60 minutes are not included in the graphs. The error bars are the standard deviations based on 3 replicates. The Taguchi trendlines are included in Figure 6.20 and the associated influence of each parameter at different times is is shown in Figure 6.21.

Interpretation

The cumulative water evaporation of all mix designs after 14 days is not equal to the cumulative water absorption after 14 days. This means that the samples contain water after the testing period of 14 days. Mix design C1.3 and C1.4 have approximately reached equilibrium conditions after 14 days in the climate chamber and do contain 48.2 g/L and 55.5 g/L after 14 days in the climate chamber. This means that approximately half of the absorbed water is not evaporated at the end of the test. Since equilibrium is reached, this water will not evaporate under the given conditions, even if the evaporation test is elongated. Mix design C1.1 and C1.2 have not reached equilibrium conditions at the end of the experiment and still contain 95.2 and 121.2 g/L respectively. This amount will reduce before equilibrium is reached, but looking at the trend of the graph, this value will most likely remain a bit higher than that of mix design C1.3 and C1.4.

The standard deviations for the water evaporation rate are high as is seen in Figure 6.19b. Unlike the water evaporation rate graphs of the cement paste samples and the water absorption rate graphs of the pervious concrete samples, the graphs are highly fluctuating. This is explained by the fluctuating temperature and humidity in the climate chamber at the time of doing the evaporation test on the first series of pervious concrete.

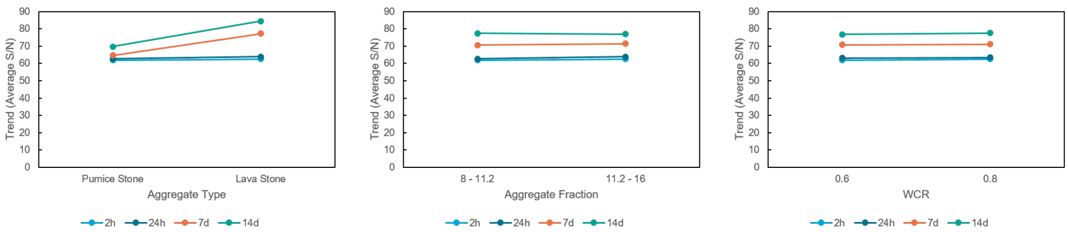
At the starting phase of the experiment (at 2 hours and 24 hours), the Taguchi trendlines are all horizontal indicating that non of the parameters has a significant effect on the water evaporation rate. However, the Taguchi trendlines for the aggregate type at 7 days and 14 days are not horizontal anymore. Pervious concrete with lava stone aggregate has a lower evaporation rate after 7 and 14 days. This is explained by the fact that pervious concrete samples with lava stone have reached equilibrium conditions after 7 days, meaning that the moisture content does not change anymore. Furthermore, the samples made with lava stone aggregate contained less water at the start of the evaporation test, which



(a) Cumulative water evaporation

(b) Water evaporation rate

Figure 6.19: Water evaporation characteristics of the first series of pervious concrete samples in climate chamber (T = 20 ± 2 °C, RH = 55 ± 5 %)



(a) Influence of aggregate type (b) Influence of aggregate fraction (c) Influence of WCR

Figure 6.20: Taguchi trends for the water evaporation rate

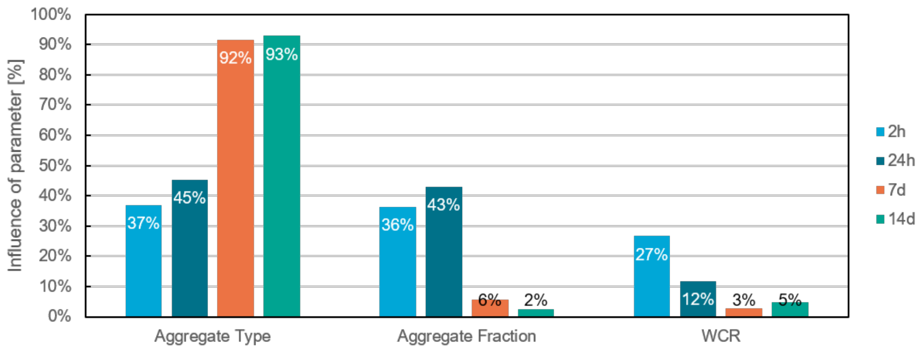


Figure 6.21: Influence of each mix design parameter on the water evaporation rate at different time frames

makes it logical that the water evaporation rate is eventually also lower. It should be noted that the cement paste layer in the mix designs with pumice stone is thinner ad is explained in paragraph 6.2.1 and Appendix B. This can also partly explain the fact that the aggregate type is indicated as a important parameter for the water evaporation rate.

Conclusion
It is concluded that at a temperature of 20 ± 2 °C and a relative humidity of 55 ± 5 %, the samples contain a certain amount of water when they have reached equilibrium. As expected, the mix designs that performed the best for the water absorption rate scored the worst for the water evaporation rate. The fact that this difference is hardly visible in the first 24 hours, shows that the difference is mostly caused by the difference in initial water absorption. As a high initial water absorption is preferred in this investigation, the mix designs are not adjusted to decrease the water evaporation rate.

6.2.6. Freeze-thaw durability

Results
The cumulative mass loss as percentage of the total weight of the sample during FT cycles in included in Figure 6.22. The error bars represent the standard deviations based on two measurements. One measurements included the weight loss of two cubes as two cubes are placed in one container. Taguchi trendlines are made for the mass loss during FT cycles at different amount of cycles and are presented in Figure 6.23. The influence of each mix design parameter on the freeze-thaw durability at different amount of cycles is shown in Figure 6.24. The influence of the 3 mix design parameters combined adds up to 100%.

Interpretation
As all cubes have completely failed after 18 cycles, the test is stopped at that time. At 4 cycles there is a clear gap between the performance of mix designs C1.1 and C1.2 and the mix design C1.3 and C1.4. The mass loss of the mix designs containing pumice stone aggregate is much higher than the ones containing lava stone aggregate. This difference remains clearly visible at the 6 cycles mark. After 4 cycles mix designs C1.1 and C1.2 already exceed the limit of 25% of mass loss, meaning that the freeze-thaw durability is less than 4 cycles when the boundary of 25% is used. Mix design C1.3

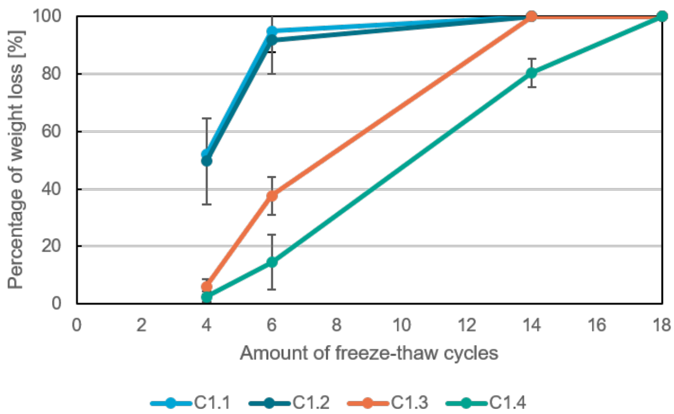
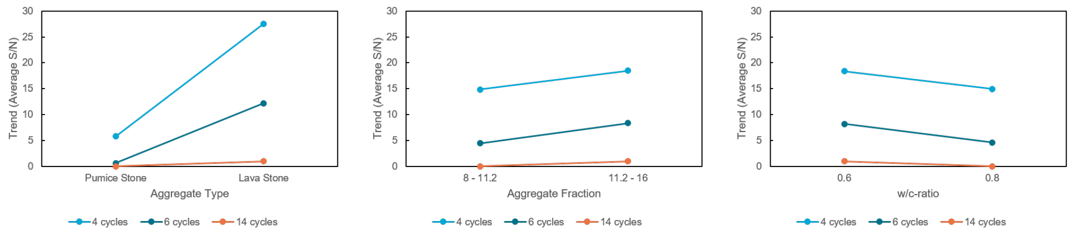


Figure 6.22: Cumulative mass loss during FT cycles



(a) Influence of aggregate type (b) Influence of aggregate fraction (c) Influence of WCR

Figure 6.23: Taguchi trends for the freeze-thaw durability

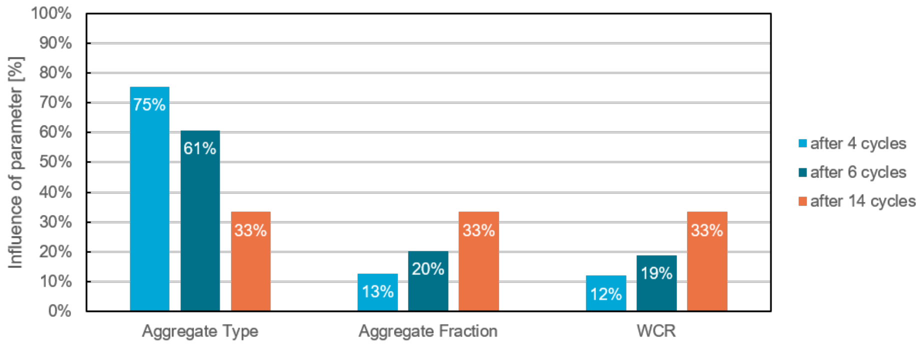


Figure 6.24: Influence of each mix design parameter on the mass loss due to FT cycles after different amount of cycles

exceeds the mass loss limit after 6 cycles, meaning that the freeze-thaw durability is between 4 and 6 cycles. Mix design C1.4 has the highest freeze-thaw durability of approximately 7 cycles, before reaching the mass loss limit. This means that a significant improvement is needed for the mix designs tested in this investigation to obtain a mix design with appropriate freeze-thaw durability.

At 14 and 18 cycles only the samples of C1.4 are not completely broken down. Therefore this measurement is not suitable for fair comparison of the influence of the parameters on the freeze-thaw durability. This is seen in Figure 6.23 from the fact that all lines for the 14 cycles measurement point are almost horizontal. The trendlines associated to 4 and 6 cycles are more relevant and show a visible impact of the design parameters on the objective. The aggregate type is clearly influencing the freeze-thaw durability the most with 78% and 61% after 4 and after 6 cycles, respectively. Again this difference is also associated to the thinner cement paste layer in the samples with pumice stone aggregate (paragraph 6.2.1). At the 6 cycle point there is also a visible difference between C1.3 and C1.4. This difference can be caused by the smaller fraction of C1.3 or by the higher WCR of C1.3. Although this is not confirmed by the Taguchi trendlines it is more plausible that this difference is caused by the higher WCR, since a higher WCR results in a more porous and weaker cement layer. The failure pattern in Figure 6.25 shows, that failure of the cement layer is causing the mass loss during FT cycles. A weakened cement layer is thus associated to the freeze-thaw durability. Additionally, in literature the WCR is indicated as the most important factor for freeze-thaw durability.

Conclusion
The results confirm that the freeze-thaw durability of pervious concrete cannot be evaluated in the same way as conventional concrete, as the mass loss is in a completely different order of magnitude. As the pervious layer is a non structural layer the maximum acceptable mass loss after a certain amount of FT cycles can be higher than zero. In the Netherlands, the freezing temperatures are usually not lower than -10 °C and the freezing cycles are less severe than in the testing set up. More research is needed to determine an appropriate mass loss limit and number of cycles for freeze-thaw testing of non-structural pervious concrete for applications in the Netherlands.

Although a certain amount of mass loss during FT cycles is acceptable, complete failure of the cubes after approximately 6 cycles is never justifiable. The mix design is thus adjusted to improve the freeze-thaw durability. As the aggregate type is the most contributing factor to the freeze-thaw durability and significant improvement is needed, pumice stone aggregate is not included in the mix designs in the second series of pervious concrete, despite its positive effect on the water absorption characteristics. All mix designs are made with coarse lava stone aggregate. From the compressive strength testing it is already concluded that a thicker cement paste layer is needed to improve the compressive strength and it is expected that this will also positively effect the freeze-thaw durability. The effect of the WCR on the freeze-thaw durability did not become clear from the results of the first series. As this parameter is expected to have a high influence on the freeze-thaw durability and a lower WCR value might be needed to obtain a mix design with appropriate freeze-thaw durability, the second series will vary the WCR parameter on a wider range namely from 0.4 to 0.8.

6.2.7. Conclusion 1st series of pervious concrete phase

Non of the tested mix designs fulfils the compressive strength requirement of 6 MPa and the mix designs are thus not suitable for implementation as finishing layer of a quay wall. The failure patterns showed that the cement paste bond should be strengthened. Apart from the too low compressive strength, the freeze-thaw durability of all mix designs is lower than the freeze-thaw durability of the mix design made by Holcim Bouw&Infra. Therefore the freeze-thaw durability needs to be improved as well. Improving the strength of the cement bond will also improve the freeze-thaw durability as failure of the bonds is the main cause for failure during FT cycles. The cement bond is strengthened by increasing the cement paste content, which is possible as the void ratios are far above the minimum interconnected porosity requirement of 18%. Furthermore, a WCR of 0.4 is included as this also results in a stronger cement paste, which is most likely needed to sufficiently increase the compressive strength. The first series showed that the use of two aggregate materials is error sensitive and varies parameters such as the porosity unintentionally. Therefore the aggregate type is not varied in the second series of pervious concrete. As the freeze-thaw durability of the mix designs including pumice stone is remarkably low,

(a) Leftover cubes of C1.1 after 4 cycles

(b) Leftover cubes of C1.4 after 4 cycles

(c) Completely broken down cubes of C1.1 after 6 cycles

(d) Leftover cubes of C1.3 after 6 cycles

Figure 6.25: Images of failure due to FT cycles

it is assumed that the two methods to increase the bond strength are not enough for improving the freeze-thaw durability of the mix designs with the desired extend. Therefore pumice stone is not used as an aggregate material in the second series of pervious concrete. The first series of pervious concrete shows that a thin cement paste layer with a WCR of 0.6 or 0.8 is water permeable and is not preventing water absorption in the aggregate material. The second series should determine if the same applies for a thicker cement paste layer with a lower WCR of 0.4.

6.3. Results of the 2nd series of pervious concrete

6.3.1. Porosity

Results

For the three mix design of the second series the void ratios are provided in Figure 6.26. Only the interconnected macro-pores are included in this value. The error bars are the standard deviations based on 3 replicates.

Interpretation

The void ratio of all tested mix designs is above the minimum void ratio of 18%. The mean void ratio differs a bit for the mix designs, but taking into account the standard deviations no significant difference is observed. This means that the porosity is hardly influencing the other tested properties. The error bars of the second and third mix design comply with the standard deviations of most mix designs in the first series. This can be explained by the hand compaction method that results in heterogeneous samples. The error bars are wider than of the first mix design. The low standard deviation of C2.1 is probably coincidence, since the hand compaction method is also used for casting of those samples.

Conclusion

The void ratio of the mix designs is above the minimum interconnected void ratio of 18%. This indicates that it is possible to increase the cement paste volume compared to the first series and still fulfil the

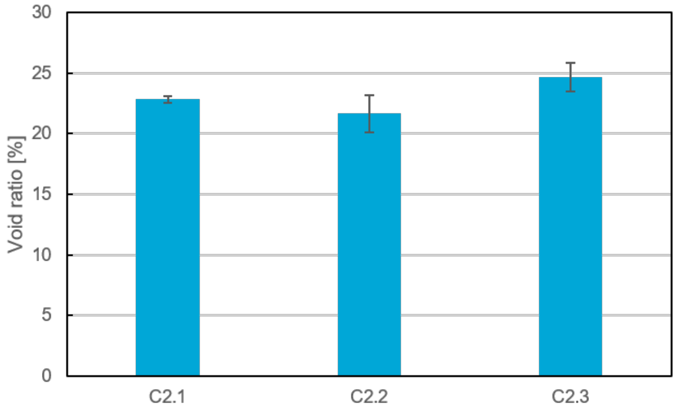


Figure 6.26: Void ratio of the second series of pervious concrete

interconnected porosity requirement demanded by the vegetation. There is no significant difference between the void ratio of the mix designs in this series, so the porosity is not unintentionally effecting the other properties.

6.3.2. Compressive strength

Results

The results of the compressive strength development of the three pervious concrete mixtures after 3, 7 and 28 days of curing are provided in Figure 6.27. The error bars are the standard deviations based on 3 replicates. An image of the failed samples tested after 28 days of curing is included in Figure 6.28.

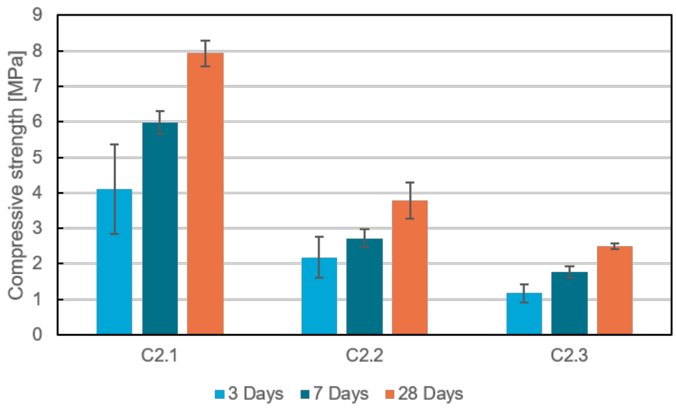
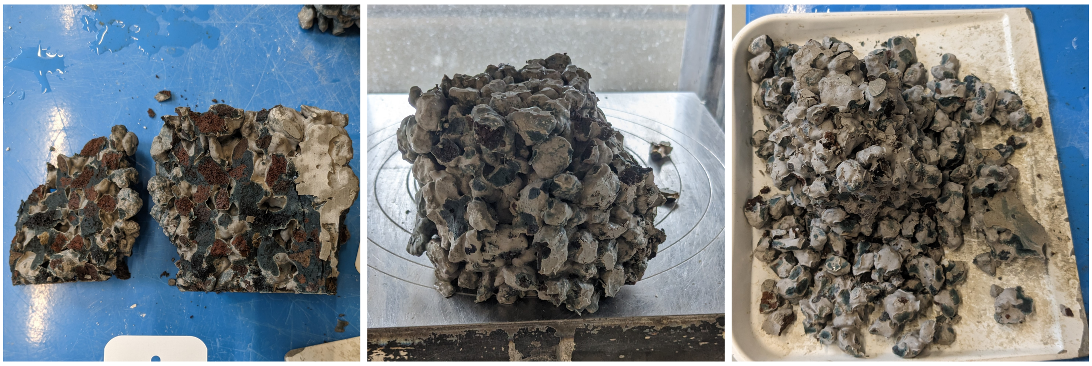


Figure 6.27: Compressive strength development of the second series of pervious concrete samples under different curing ages

Interpretation

Only C2.1 reaches the compressive strength requirement of 6 MPa after 28 days of curing. The other mix design are thus not suitable, unless the compressive strength requirement is lowered. The lower compressive strength of C2.2 and C2.3 is caused by the higher WCR, resulting in a more porous cement layer. The porosity is related to the strength of the cement paste, therefore the cement bonding between the aggregates is the strongest in the mix design with the lowest WCR. The images of the failed specimens confirm that the difference in compressive strength is caused by the difference in strength of the cement layer. The C2.1 sample failed mostly due to failure of the aggregate. The leftover material are big pieces, unlike the leftover material of the C2.3 test, which is completely broken down in single aggregates. In this case the failure is mostly caused by failure of the cement paste. The C2.2 sample is in between those two failure patterns: some of the aggregate material is fallen off as single aggregates, while the big leftover remains in one piece.



(a) C2.1 (b) C2.2 (c) C2.3

Figure 6.28: Failure pattern of compressive strength testing at 28-day curing age

The results for the compressive strength development of the second series of pervious concrete, are compared to the results for the compressive strength development of the hardened cement mortar to determine if there is a relation between the compressive strength of the cement mortar and the pervious concrete for different WCRs. The 28-day compressive strength of the cement mortar with a WCR of 0.6 and 0.8 is 49.2% and 27.6% of the compressive strength of the cement paste with a WCR of 0.4, respectively. The 28-day compressive strength of the pervious concrete with a WCR of 0.6 and 0.8 is 47.8% and 31.4% of the compressive strength of the pervious concrete with a WCR of 0.4, respectively. Although those values are not exactly the same, they are close together which suggests that the compressive strength of the cement mortar is related to the compressive strength development of pervious concrete. The compressive strength of the mortar is used instead of the compressive strength of the cement paste, as the results of the mortar samples have a much lower standard deviation.

Conclusion

C2.1 is the only mix design that is appropriate for this application according to the 28-day compressive strength requirement. Improving the compressive strength of the mix designs with WCRs above 0.4 by increasing the cement paste volume is not possible as the interconnected porosity requirement is probably not reached if cement paste volume is increased. Other ways to improve the strength of the cement paste include the addition of admixtures and fillers, but since those methods reduce the porosity of the cement paste, which is the exact reason why the high WCRs are chosen, it seems impossible to increase the porosity of the cement paste layer, while assuring a sufficient bonding strength. If water flow through the cement paste to the aggregate material is possible with this restriction, should be evaluated with the other experiments. In this way it is concluded if material modification is possible to increase water characteristics of the pervious concrete. If this is not the case, the water characteristics should solely be improved by system modifications.

6.3.3. Water absorption

Results

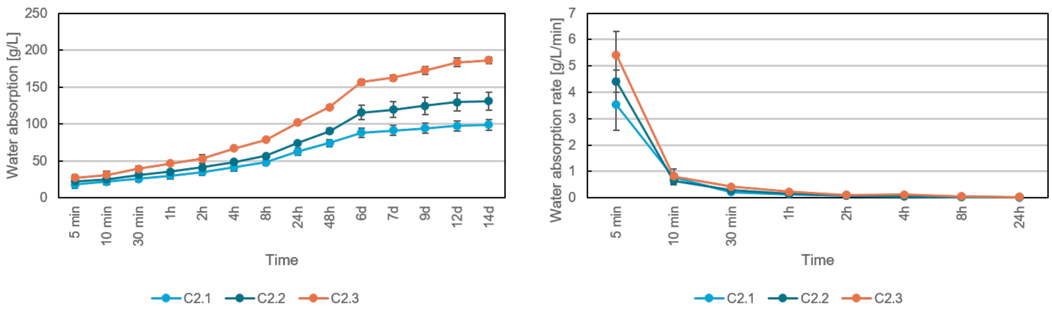
The maximum water absorption capacity of the three pervious concrete mixtures is determined by total immersion in water and is provided in Table 6.4. The cumulative water absorption of the three mixtures is provided in Figure 6.29a for immersion in a small layer of water. From the cumulative water absorption the water absorption rate is determined by dividing the difference in water absorption per time frame by the time between the measurements. The results are included in Figure 6.29b. The error bars are the standard deviations based on 3 replicates.

Interpretation

Based on the water absorption of the cement paste and the water absorption of the raw aggregate after 14 days, the theoretical maximum water absorption capacity of the pervious concrete is estimated. The cement paste layer is assumed permeable to ensure water flow through the layer to the aggregates in all mix designs. The results are included in Table 6.5. The maximum water absorption capacity found

Table 6.4: Water absorption capacity of the mix design of the second series of pervious concrete. Standard deviation is based on three replicates per mix design.

	Maximum water absorption capacity [g/L]	Standard deviation [g/L]
C2.1	188.8	1.1
C2.2	222.6	3.2
C2.3	234.3	1.3



(a) Cumulative water absorption

(b) Water absorption rate

Figure 6.29: Water absorption characteristics of the second series of pervious concrete samples immersed in a small layer of water

by testing is 91.0%, 94.9% and 93.2% of the theoretical value, meaning that the theoretical values are slightly higher. However, as the differences in percentages for the different mix designs are small, it is suggested that the WCR is not effecting the water absorption of the aggregate material above a value of 0.4. The hypothesis that a WCR of 0.4 causes an impermeable layer around the aggregate is thus not true for the maximum water absorption capacity. The maximum water absorption capacity of mix design C2.2 and C2.3 is respectively 17.9% and 24.1% higher than of mix design C2.1. The increase is attributed to the higher water absorption in the cement paste layer, due to a higher volume of pores in this layer.

Equilibrium conditions are approximately reached after a testing period of 14 days, which means that the maximum water absorption capacity is not reached when the sample is immersed in a small layer of water. The percentage of the water absorption capacity reached after 14 days is 52.3%, 58.8% and 79.6% for mix designs C2.1, C2.2 and C2.3, respectively. The upper part of the cube can probably not absorb the same amount of water as for complete immersion in water, as water supply is depended on the vertical transport due to capillary effect in the pervious concrete. This capillary effect is depended on the capillary pores in the cement paste layer, as the diameter of the macro-pores is too big for capillary suction. Since the cement paste with a higher WCR has more capillary pores, the capillary water transport is better resulting in a higher percentage of the maximum water absorption capacity reached in 14 days. This effect is especially visible in the mix design with a WCR of 0.8 and to a lesser extent in the mix design with a WCR of 0.6.

Table 6.5: The theoretical maximum water absorption capacity of 1L of pervious concrete based on the volume of the three elements and the water absorption capacity of the lava stone aggregate and the cement paste mix designs after 14 days

	Volume [L]	Water absorption [g/L]		
		C2.1	C2.2	C2.3
Cement paste	0.25	99.1	126.2	143.0
Aggregate	0.52	108.4	108.4	108.4
Macro-pores	0.23	0	0	0
Total	1	207.5	234.6	251.4

Conclusion

Water absorption of the aggregate is possible in the pervious concrete samples regardless of the WCR, meaning that a WCR of 0.4 results in a permeable cement paste layer surrounding the aggregate. The increase in cement coating thickness compared to the first series, did thus not reduce the permeability to such an extent that the aggregates cannot absorb water anymore. The increase of the maximum water absorption capacity of the pervious concrete mix designs with a higher WCR is attributed to the difference in water absorption in the cement layer itself due to higher porosity of that layer. However, when not completely immersed in water the WCR has a significant influence on the water absorption rate. This is a result of the higher capillary suction in cement pastes with a higher WCR. This is a problem for the freeze-thaw durability of those mix designs.

6.3.4. Water evaporation

Results

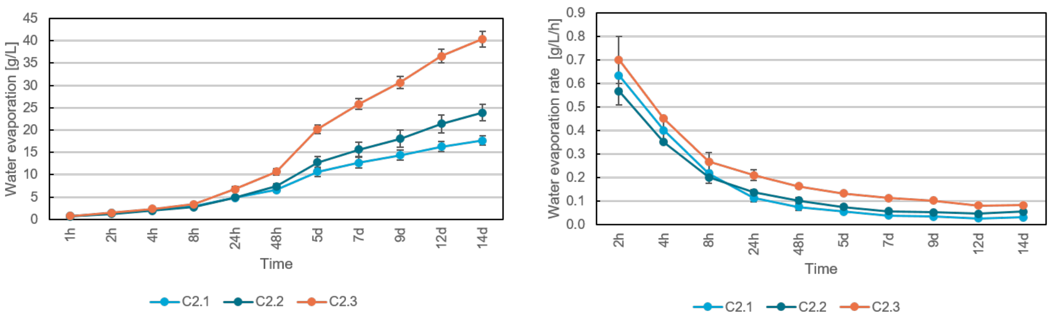
The cumulative water evaporation of the three mixtures is provided in Figure 6.30a for a constant temperature (20 ± 2 °C) and a constant humidity (55 ± 5 %). From the cumulative water evaporation the water evaporation rate is determined by dividing the difference in water evaporation per time frame by the time between the measurements. The results are included in Figure 6.30b. The error bars are the standard deviations based on 3 replicates. The early measurements up till 4 hours are close to zero, but have relatively high standard deviations. Some earlier measurements are done before the 2 hour mark, but as this would lead to a long flat beginning of the evaporation graph and higher standard deviations, the first 4 measurements points at 5, 10, 30 and 60 minutes are not included in the graphs.

Interpretation

The cumulative water evaporation of all mix designs after 12 days is not equal to the cumulative water absorption after 14 days. This means that the samples contain water after the testing period of 12 days. The mix designs have not yet reached equilibrium conditions after 12 days in the climate chamber and contain 82.4 g/L, 109.5 g/L and 149.8 g/L respectively for mix design C2.1, C2.2 and C2.3 after 12 days in the climate chamber. This means that approximately 80% of the absorbed water is not evaporated after 12 days. For mix design C1.3 and C1.4 of the first series only 50% of the absorbed water is not evaporated after 14 days. Although more parameters are varied between the mix designs of the first and the second series, the most important difference is the difference in cement paste volume. The lower porosity and the thicker cement paste layer explain why the water evaporation for the second series is slower. Since equilibrium is not reached, more water will evaporate for the given conditions if the evaporation test is elongated. The trend of the graph shows that approximately 70 % of the absorbed water is not evaporated at equilibrium.

Conclusion

It is concluded that at a temperature of 20 ± 2 °C and a relative humidity of 55 ± 5 %, the samples contain a certain amount of water when they have reached equilibrium. As expected, the mix designs that performed best for the water absorption rate scored the worst for the water evaporation rate. The



(a) Cumulative water evaporation

(b) Water evaporation rate

Figure 6.30: Water evaporation characteristics of the second series of pervious concrete samples in climate chamber (T = 20 ± 2 °C, RH = 55 ± 5 %)

fact that this difference is hardly visible in the first 24 hours, shows that the difference is mostly caused by the difference in initial water absorption. Increasing the thickness of the cement paste layer and reducing the porosity have a decreasing effect on the water evaporation.

6.3.5. Freeze-thaw durability

Results

The cumulative mass loss as percentage of the total weight of the sample during FT cycles in included in Figure 6.31. The error bars represent the standard deviations based on two measurements. One measurements included the weight loss of two cubes as two cubes are placed in one container.

Interpretation

Only mix design C2.3 has completely failed after 18 cycles, therefore the testing time for mix design C2.2 and C2.3 is elongated to 28 cycles. At 4 cycles the mass loss of all mix designs is small, but after more than 6 cycles the results diverge for the three mix designs. A boundary of 25% of mass loss is set for the freeze-thaw durability. Mix design C2.3 is clearly performing worst and the mass loss boundary of 25% is reached after less than 8 cycles. This is in accordance with the water absorption results, that also showed that capillary water absorption in this mix design is significantly higher than for the other mix designs. After 18 cycles, mix design C2.2 slightly exceeds the mass loss limit of 25%, meaning that the freeze-thaw durability is under performing, but due to the sensitivity of the determination of the mass loss limit, this mix design is not disregarded based on its freeze-thaw durability. The freeze-thaw durability of mix design C2.1 is excellent and the mass loss is almost equal to zero up till 18 cycles of testing. After 28 FT cycles the mass loss is below 10%.

The effect of the aggregate fraction of the first series is negligible according to the conclusions of that phase. Therefore it is assumed that the difference in results between C1.3 and C2.3, which have the same WCR, is solely caused by the increase of the cement paste content. The same applies for comparing mix design C1.4 with mix design C2.2. When comparing the freeze-thaw testing results of the second series with the results of the first series, it is obvious that the cement paste content, has great influence on the freeze-thaw durability.

Conclusion

The results confirm that the freeze-thaw durability of pervious concrete is enhanced by decreasing the ACR. Furthermore the WCR is influencing the freeze-thaw durability strongly due to the capillary pores in the cement paste with high WCRs. Mix designs with a WCR between 0.4 and 0.6 and an ACR equal to 2 are suitable as pervious concrete layer based on the freeze-thaw results and the assumption of a 25% mass loss boundary at 18 cycles.

6.3.6. Conclusion 2nd series of pervious concrete phase

Increasing the cement paste volume positively effects the compressive strength and the freeze-thaw durability whilst fulfilling the interconnected porosity requirement. However, only the mix design with a

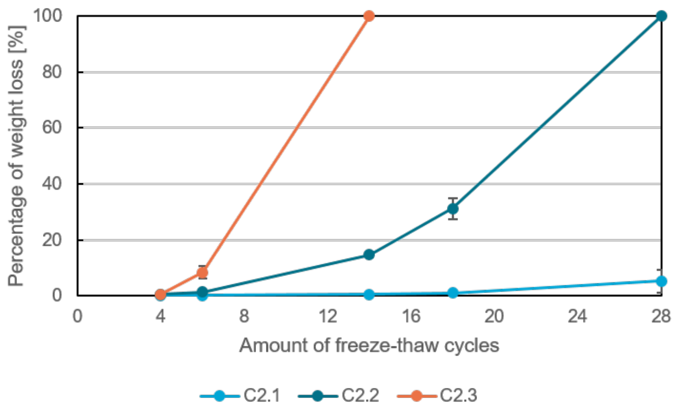


Figure 6.31: Cumulative mass loss during FT cycles of mix designs of the second series of pervious concrete

WCR of 0.4 fulfils the compressive strength requirement. The freeze-thaw durability of this mix design is excellent. The cumulative water absorption of this mix design is slightly lower compared to the mix designs with a higher WCR, but this is primarily attributed to the difference in the water absorption of the cement paste layer. Water absorption of the aggregate material is thus independently of the WCR despite of the thicker cement layer. However, the percentage of the maximum water absorption capacity reached when the sample is in contact with a small layer of water is influenced by the WCR. A higher WCR leads to better capillary suction in the cement paste layer, which causes the water absorption to be closure to the maximum water absorption capacity. To increase the maximum water absorption capacity and to obtain better capillary suction in the mix design with a WCR of 0.4, soil is added to the macro-pores in the next phase. Regardless of the results including soil, the use of porous lava stone aggregate material is recommended for improving water retention in pervious concrete.

6.4. Results of mix design C1.4 with soil

6.4.1. Water absorption

Results

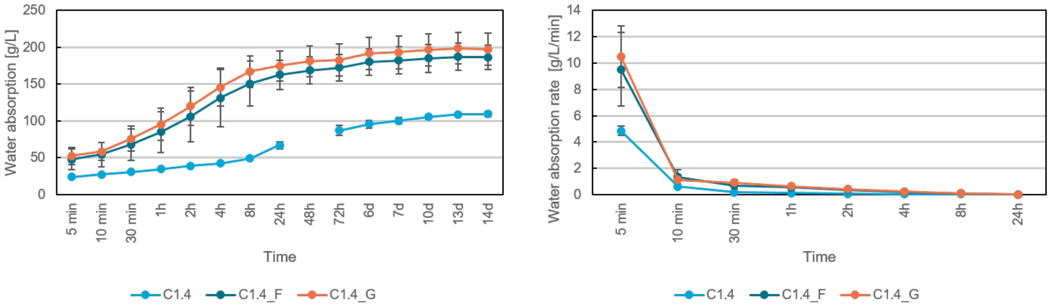
The maximum water absorption capacity of mixture C1.4 including fine and coarse soil is determined by total immersion in water and is provided in Table 6.6. The maximum water absorption of the C1.4 mixture without soil which is determined during the first series of pervious concrete is added as reference. The cumulative water absorption when immersed in a small layer of water of the samples with fine and coarse soil is provided in Figure 6.32a. From the cumulative water absorption the water absorption rate is determined by dividing the difference in water absorption per time frame by the time between the measurements. The results are included in Figure 6.32b. The error bars are the standard deviations based on 3 replicates except for C1.4/F where the standard deviations are based on two replicates. The reason for this is the fact that a lot of soil is visibly removed from sample C1.4/F1 after immersion in water. This results in lower water absorption values compared to the other two cubes of C1.4/F and thus leads to high standard deviations when included. Therefore the results of C1.4/F1 are not taken into account in the graphs.

Interpretation

The standard deviations of the maximum water absorption capacity, the cumulative water absorption and the water absorption rate are much higher for the test results including soil than for the test results without soil. The first reason for the high standard deviations is that completely filling all the macro-pores with soil is very difficult. Although the macro-pores are interconnected, replacing the air by soil is not completely possible. That there is still a lot of air in the pores at the start of the experiment is observed when the cubes are immersed in water and air bubbles appeared at the water surface. The percentage of the pores that is initially filled with soil is unknown, but probably differs per sample. Besides the fact that not all pores are initially filled with soil, the soil mixture is flowing out of the pores after immersion in water despite of the glue that is added to the soil. As is visible in the image in Figure 6.33, the pores at the surface are completely filled with soil before the start of the experiments. However, after the cubes are immersed in water, the soil at the surface is visibly removed as shown in Figure 6.34. The amount of soil that is flown out differs per sample, which also contributes to the high standard deviations. In future research the testing method should be adapted to improve the accuracy of the results. One way to improve this is to ensure that the glue added to the soil is working properly. Due to the vacuum that is applied to insert the soil mixture in the macro-pores, water evaporates too quickly from the soil mixture, causing an incomplete reaction of the glue. The glue namely needs water

Table 6.6: Maximum water absorption capacity of mix design C1.4 without soil (C1.4), with fine soil (C1.4/F) and with coarse soil (C1.4/G). The average and the standard deviation are based on three replicates per type except for C1.4/F which is based on two replicates.

	Water absorption capacity [g/L]	Standard deviation [g/L]
C1.4	174.0	6.9
C1.4/F	220.6	33.0
C1.4/G	250.3	22.7



(a) Cumulative water absorption

(b) Water absorption rate

Figure 6.32: Water absorption characteristics of mix design C1.4 without soil, with fine soil and with coarse soil immersed in a small layer of water

Figure 6.33: Images of the cubes with soil before the first experiment is conducted

(a) C1.4/F1 (b) C1.4/F2 (c) C1.4/F3

(d) C1.4/G1 (e) C1.4/G2 (f) C1.4/G3

Figure 6.34: Images of the cubes with soil after immersion in water to determine the maximum water absorption capacity

for a proper reaction just as cement does. Some preliminary testing is done with vacuum suction for a shorter period (5 min instead of 10 min), which seems to improve the working of the glue. More testing is needed to validate this. Furthermore, other techniques can also be considered for inserting the soil mixture to the macro-pores. However, those techniques usually have the disadvantage that it is even more difficult to fill the deeper macro-pores. For improving the accuracy of the testing, the cubes can also be wrapped by a material which allows for the passage of water, but does not allow the passage of small soil particles (like a filter). In this way more accurate test results can be obtained, but the outflow of soil from the pervious concrete in the eventual application is not solved this way.

The cumulative water absorption graphs show a similar trend. There is a gap between the graphs from the samples with and without soil. This can easily be explained by the ability of the soil to hold water. In contrast, empty macro-pores cannot hold water, due to the high permeability which ensures outflow of water from the macro-pores. Since the percentage of macro-pores filled with soil is unknown, but is most certainly lower than 100%, the water holding potential of the substrate layer, when completely filled with soil cannot be determined, but is higher than the measured values.

As the water absorption rate is almost equal to zero at 14 days, equilibrium is reached at the end of the testing period. The water absorbed at the end of the cumulative water absorption test is lower than the maximum water absorption. However, for C1.4/F and C1.4/G respectively 84.6% and 78.8% of the maximum water absorption is absorbed at the end of the testing period. For C1.4 without soil, this value is equal to 62.9%. This difference indicates that adding soil to the pores, is also beneficial for the water absorption by the pervious concrete itself, when only one side of the pervious concrete is immersed in water. Reason for this is the capillary effect in the soil, while there is no capillary suction in the macro-pores as the diameter of those pores is too large.

Conclusion

Although the testing method has to be changed to obtain more accurate results and to be able to exactly quantify the water absorption due to the addition of soil, it is concluded that water absorption characteristics improve due to the addition of soil to the macro-pores. There is no significant difference between the water absorption in the samples with fine and coarse soil. However, the outflow of fine soil material is possibly higher than the outflow of coarse soil material. Additional testing must prove if this difference is also visible for an increased number of samples. If this is proven, the use of coarse soil is recommended.

6.4.2. Water evaporation

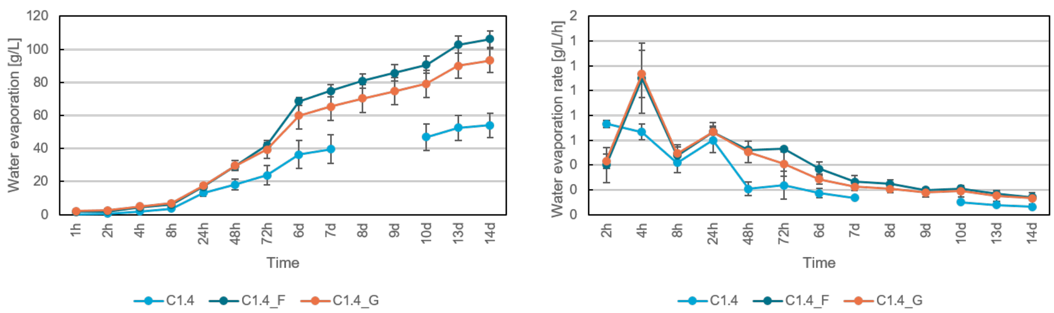
Results

Figure 6.35 shows the cumulative water evaporation and the water evaporation rate over time. The error bars are the standard deviations based on 3 replicates except for C1.4/F. The standard deviations of C1.4/F are based on two replicates. The reason for this is the fact that a lot of soil is visibly removed from sample C1.4/F1 after immersion in water as explained in the paragraph 6.4.1. Therefore the results obtained for this sample are not reliable and are not included in the graphs. The early measurements up till 8 hours are close to zero and have relatively high standard deviations. Some earlier measurements are done before the 2 hour mark, but as this leads to a long flat beginning of the evaporation graph and higher standard deviations, the first 4 measurements points at 5, 10, 30 and 60 minutes are not included in the graphs.

Interpretation

The cumulative water evaporation after 14 days is not equal to the cumulative water absorption after 14 days for all sets. This means that the samples contain water after the testing period of 14 days. C1.4/F and C1.4/G have almost reached equilibrium conditions in the climate chamber after 14 days and contain 80.4 g/L and 104.1 g/L at the end of testing respectively. This is equal to 44.9 % and 52.8% of the initial water content at the start of the test. As equilibrium is almost reached, most of this water will not evaporate under the given conditions, even if the evaporation test is elongated. C1.4 reaches equilibrium conditions during the testing period as is already discussed in paragraph 6.2.5. After 14 days in the climate chamber mix design C1.4 contains 55.5 g/L, which is equal to 50.7% of its initial water content at the start of the evaporation test. The cumulative water evaporation is higher for the mix designs with soil, but the previously mentioned values show that the water content is almost half of the initial value for all mix designs. This means that the difference in the cumulative water evaporation graph is caused by the higher water content at the start of the evaporation experiment for the sets with soil.

The water evaporation rate graph is highly fluctuating as is also seen for the evaporation rate graphs for the first series of pervious concrete without soil. This is explained by the fluctuating temperature and humidity in the climate chamber at the time of doing the evaporation test. Furthermore, the time steps between the early measurements of the evaporation test are too small. For the given conditions in the climate chamber, the evaporation rate is low, which means that the measurements are close together. The weighing method includes an error, due to the weighing measurements that are used. As the differences are very small due to the short time frames between the measurements, the error of the weighing device plays a more prominent role, than when the difference in measurements are higher.



(a) Cumulative water evaporation

(b) Water evaporation rate

Figure 6.35: Water evaporation characteristics of mix design C1.4 without soil, with fine soil and with coarse soil in climate chamber (T = 20 ± 2 °C, RH = 55 ± 5 %)

This creates the high standard deviations which can be seen at the early measurements in Figure 6.35b. Due to the fluctuations and the high standard deviations, it is difficult to use the evaporation rate graph to determine the effect of the WCR on the evaporation rate. The graphs from the sets with soil are somewhat higher, which is also explained by the higher original water content.

Conclusion

It is concluded that at a temperature of 20 ± 2 °C and a relative humidity of 55 ± 5 %, the samples contain a certain amount of water when they have reached equilibrium. As expected, the sets with soil that performed the best for the water absorption rate, performed the worst for the water evaporation rate. The fact that the water content as a percentage of the initial water content is the same at the end of the experiment, shows that the difference is mostly caused by the difference in initial water absorption. As a high initial water absorption is preferred in this investigation, the use of soil in the macro-pores is recommended.

6.4.3. Conclusion of soil phase

It is concluded that the percentage of the maximum water absorption capacity that is reached for a sample that is in contact with a small layer of water is influenced by the addition of a soil mixture. This is explained by the capillary suction of the soil in the macro-pores. The same phenomenon is seen for a higher WCR, but due to the negative effect of a high WCR on the strength and durability properties, a high WCR cannot be implemented. The fact that soil can also contribute to the capillary effect, makes increasing the WCR completely unnecessary. Coarse soil is recommended as the outflow of soil from the surface pores is lower for coarse soil compared to fine soil.

7

Discussion, conclusion and recommendations

7.1. Discussion

The results of the cement paste samples show that for pastes with increased WCR, the performance decreases for the compressive strength development and the final setting time. The water absorption and the water absorption rate in the first 30 minutes are higher for higher WCRs. As it is not exactly known to what degree the compressive strength of the cement paste determines the compressive strength of the pervious concrete and the objective of this thesis is to increase the water absorption, the high WCRs are not excluded from the mix designs of pervious concrete, despite of their negative side effects.

The results of the first series of pervious concrete show that the water absorption of the pervious concrete is mostly influenced by the aggregate type. It showed that pumice stone aggregate increases the water absorption compared to lava stone aggregate, which is in accordance with the water absorption of the raw aggregate material. It indicates that an aggregate with higher water absorption is beneficial for the water absorption capacity of pervious concrete. However, the Taguchi trendlines for the compressive strength and the freeze-thaw durability show that changing the aggregate type from lava stone to pumice stone, reduces the compressive strength and the freeze-thaw durability considerably. Increasing the water absorption of pervious concrete by using an aggregate type with a higher water absorption thus has negative side effects for the strength and durability properties. The trends from the Taguchi analysis cannot solely be attributed to the aggregate type, but are also caused by the thinner cement paste layer in the samples with pumice stone aggregate. Only 66% of the cement paste volume used for the lava stone mixtures is namely used for the pumice stone mixtures, due to a false assumption for the dry particle density and the water absorption of the pumice stone. This error is discussed in more detail in Appendix B. No significant influence is seen in the Taguchi trendlines for the water absorption associated to the aggregate fraction, as the range chosen for the aggregate fraction parameter is too small. It would have been better to use the full factorial method with a constant aggregate fraction instead of the Taguchi method with a varying aggregate fraction. The WCR has no significant influence on the water absorption, because of the too thin layer of the cement paste, which results in a water permeable layer independently of the WCR of the cement paste. That the cement layer is too thin is confirmed by the compressive strength results, which are outside the range which is set for pervious concrete (2.8 - 28.0 MPa) (*522R-10: Report on Pervious Concrete*, 2010). Apart from the compressive strength, the freeze-thaw durability of all mix design is incredibly low. Therefore non of the mix designs of the first series can be used as pervious concrete layer of a vegetated quay wall and the mix design has to be adapted.

The strength and durability properties of the pervious concrete mix design are improved by decreasing the ACR in the second series of pervious concrete. The use of multiple aggregates in the second series is undesired since it complicates comparison of the results and it leads to many samples for testing.

Therefore the second series is only made with lava stone aggregate. This aggregate type is namely more promising for its strength and durability properties, which is important since those properties have to be improved enormously. Even though the water retention capacity of mix designs with lava stone is lower than those with pumice stone, the samples of the first series made with lava stone aggregate can retain approximately 10 volume-% of water after 14 days of one sided water contact. The maximum water absorption capacity is even higher. Combining this with a soil mixture in the macro-pores, the finishing layer can retain a considerable amount of water. If the requirements can be reached with lava stone aggregate, the use of pumice stone aggregate can be reconsidered. The results of the second series show that the compressive strength is increased by decreasing the ACR as is expected. However, only the mix design with a WCR of 0.4 fulfils the compressive strength requirement as can be seen in Table 7.1. Further increase of the compressive strength by decreasing the ACR is not possible, as this will lead to a interconnected porosity of less than 18%. This shows that increasing the porosity of the cement paste layer by increasing the WCR whilst fulfilling the strength requirement is not possible. However, the hypotheses that increasing the porosity of the cement paste layer is necessary to allow water absorption by the aggregate is falsifiable. Water transport through the cement paste is also possible for the mixture with a WCR of 0.4. A WCR somewhere between 0.4 and 0.6 is thus optimal for making pervious concrete that fulfils the strength requirements and can absorb water in the aggregate material. A higher WCR does increase the water absorption capacity slightly as more water is absorbed in the porous cement paste layer. Since the cement paste content in pervious concrete is low, optimization of the water absorption in the cement paste is not prioritized. The capillary effect that is reached by the cement paste layer with a high WCR can also be obtained by the addition of soil to the macro-pores.

The addition of soil has proven to increase the water absorption capacity of pervious concrete. The soil in the macro-pores is namely able to absorb water, while the unfilled macro-pores could not hold water due to the high permeability. Additionally, the soil appears to improve the water absorption capacity for one sided water contact by improving the capillary suction. The water retention properties can further be improved if outflow of soil is prevented. The soil is mixed with glue to prevent outflow. However, due to fast water evaporation from the soil mixture due to the vacuum used for adding the soil mixture, the glue is not properly reacting with water. Adjusting the vacuum process or using an alternative method to add the soil to the pores should be considered to improve the water retention of the pervious concrete with soil even further. As the macro-porosity of the second series is smaller than the macro-porosity of the first series, adding soil to the second series might be more difficult due to the smaller macro-pores.

In hindsight, simultaneous conduction of the experiments, resulted in improper mix-designs and illogical parameter level variations. Based on this it is advised to perform the cast the samples and perform the experiments in a succeeding order. Furthermore, the Taguchi method is useful to reduce the number of samples for a great number of varying parameters. In this research, the Taguchi method complicated analyzing, while the benefit of the reduced number of samples is minimal. Most of the experiments could have been conducted for an increased number of mix designs, except for the freeze-thaw test which is limited to testing 10 containers at once. By disregarding the mix-designs with insufficient compressive strength, the number of mix designs that should be tested for freeze-thaw durability could be minimized.

Table 7.1: Performance of the mix designs tested in the first and the second series

		Void ratio	Water absorption	Compressive strength	freeze-thaw resistance
First series	C1.1				
	C1.2				
	C1.3				
	C1.4				
Second series	C2.1				
	C2.2				
	C2.3				

Green represents good performance, yellow represents questionable performance and red represents insufficient performance

Sieving of the aggregate material is time consuming and led to the choice of minimizing the number of mix designs with the Taguchi method. Sieving of the material is needed since the aggregate materials are delivered in different fractions. Only when the aggregate is used in the delivered fraction, the sieving process could have been skipped.

7.2. Conclusion

The following conclusions are drawn from the experimental part of this investigation:

- In correspondence with the hypotheses, an increased WCR in the cement paste samples, reduces the compressive strength and increases the setting times. Therefore the compressive strength development and final setting time are important to consider when working with high WCRs. The compressive strength of cement mortar with different WCRs is closely related to the compressive strength of pervious concrete with the same WCRs.
- Increasing the porosity of the cement paste is not necessary to ensure water retention in the aggregate material of pervious concrete. This disproves the hypotheses that the cement paste layer is water impermeable when a WCR of 0.4 is used. An increased WCR does improve the water absorption of the cement paste layer, but optimization of this property is not prioritized due to the low cement content in pervious concrete. Moreover, the mix designs with WCRs higher than 0.4 did not reach the minimum 28-day compressive strength and mass loss during FT cycles was above the limit. The advice is thus to use a WCR in between 0.4 and 0.6, so the strength requirements are reached.
- Lava stone can be used as aggregate if the WCR is equal to 0.4 and the ACR is around a value of 2. The described mix design results in a 28-day compressive strength of 7.9 MPa. This is the only mix design tested in this investigation that fulfils the requirements for strength, porosity and freeze-thaw durability. The samples with pumice stone aggregate were unsuitable as finishing layer due to the low compressive strength development and the high mass losses during FT cycles. However, pumice stone aggregate is not tested in combination with a thicker cement paste layer and a WCR of 0.4, so further research is needed to determine if aggregates with a higher water absorption can be used in pervious concrete.
- The addition of soil to the macro-pores increases the maximum water absorption capacity of the pervious concrete as additional water can be absorbed in the soil in the pores. Furthermore, the soil in the pores improves the capillary suction of water, which increases the water absorption if only one side of the pervious concrete is immersed in water. This is most likely also beneficial for the application as quay wall, as the biggest part is not completely immersed in water, but is only exposed to rainwater at one side.

7.3. Recommendations

This research answers some questions with regards to the material modification of pervious concrete to increase the water absorption characteristics, but many questions remain. Therefore, the following recommendations are done for future experimental research on this topic:

Recommendations - WCR
Although this is perhaps not relevant for the development of a mix design of pervious concrete, as a WCR above 0.6 is not recommended, CT scans with a smaller voxel size, could provide more information on the pore structure of the cement paste. Additionally a mercury intrusion porosimetry test can be done. When those results are combined the effect of the WCR on the cement paste pore structure can accurately be determined.

Recommendations - Mix design
Too many parameters are varied during the first series due to a false assumption at the start of the experiments. Therefore it is difficult to determine the effect of the change in aggregate type on the properties of the pervious concrete. The results of the first series suggest that pumice stone is unsuitable as aggregate for pervious concrete, due to low compressive strength and freeze-thaw durability.

Additional testing is needed to determine if this is also the case if a WCR of 0.4 and an ACR of 2 is used, resulting in a stronger and thicker cement paste coating.

As the mass loss due to FT cycles is high for all mix designs when compared to conventional concrete, the effect of air-entraining admixtures in pervious concrete is an interesting research topic. It could increase the freeze-thaw durability of the mixtures to a certain extend, but will most likely not reach the values of conventional concrete. Standards specifically applicable on pervious concrete are developed at the moment and should be used to improve the testing methods for pervious concrete.

Recommendations - Soil mixture
For the current testing methods, the soil is inserted in the macro-pores under vacuum. As is previously discussed, water evaporates too quickly from the soil mixture due to vacuum, causing an incomplete reaction of the glue in the soil mixture. Therefore, the soil is flowing out of the macro-pores during the water absorption tests. Alternative methods for the insertion of soil into the pores or adapted settings for the vacuum tank should be considered when performing tests with soil. If no better method for insertion of the soil is found, the testing set up should be adjusted, to prevent outflow of soil when immersed in water.

The influence of the soil mixture on the compressive strength and the freeze-thaw durability is not considered. However, replacing the air in the pores by soil might effect the properties of pervious concrete. Firstly, it might be beneficial for the compressive strength, as air is replaced by soil which might help to transfer the forces. Secondly, the addition of soil does increase the water absorption and capillary suction, which can reduce the freeze-thaw durability. A study that focuses on these effects is recommended to indicate if the properties of pervious concrete are influenced as expected and to quantify the impact of the addition of soil.

Although the influence of the aggregate fraction is considered in the first series of this investigation, the chosen range is not wide enough to detect a significant influence of this parameter on the tested properties. Furthermore, the aggregate fraction is not tested in combination with the addition of soil. As the aggregate fraction influences the macro-pore structure, the relation between the fraction and the soil is an interesting research topic, which is not yet included in this investigation.

Lastly, the soil mixtures are only tested in a mix design of the first series of pervious concrete. Due to the lower cement content in this series, the macro-porosity is higher. The macro-porosity of the second series is lower, which might complicate the addition of soil to the smaller macro-pores. If the addition of soil with the vacuum method is also possible for lower macro-porosity's should be investigated in follow-up research.

III

Quay Wall Design

8

Substrate layer

Only one of the tested mix designs of the experimental part fulfils the technical requirements and can thus be implemented as pervious concrete layer in a quay wall. This is mix design C2.1, which is a mix design consisting of lava stone aggregate (fraction 8/16 mm) with a WCR of 0.4 and an ACR of 2. The results from the experimental part are used to determine if this mix design can fulfil the requirements which are set for the pervious concrete layer of the quay wall. Mix design C2.1 is not tested in combination with soil in the macro-pores, but the addition of coarse soil is recommended based on the results of mix design C1.4 with soil. Furthermore, a similar mix-design with pumice stone aggregate with a WCR of 0.4 and an ACR of 2 is not tested, but its expected performance is discussed to determine its potential as pervious concrete layer of a quay wall. If the potential is high, additional testing is recommended to validate if the requirements can be fulfilled by this mix design.

8.1. Ecological requirements

8.1.1. Moisture requirement

Five ecological requirements are mentioned in paragraph 3.1. The first ecological requirement is the moisture requirement which is the most challenging requirement as pervious concrete is only tested in irrigated situations.

Mix design with lava stone aggregate

For the moisture requirement, the maximum water absorption capacity and the water absorption and evaporation rate are important. These properties are given in Table 8.1 for mix design C2.1 and for coarse soil for climate chamber conditions (T = 20 ± 2 °C & RH = 55 ± 5 %). The properties of coarse soil are derived from the results of mix design C1.4 with and without soil. Apart from the water absorbed by the soil itself, soil influences the water absorption rate of the pervious concrete due to capillary suction of water. The difference between the samples with and without soil is therefore most significant in the early stages and decreases with time. This explains the decrease of the absorption values for longer absorption times.

The void ratio of mix design C2.1 is lower than the void ratio of mix design C1.4, meaning less soil can be added to the pores of mix design C2.1. This suggests that less water can be absorbed by the soil. On the other side, the water absorption capacity of the soil in mix design C1.4 is underestimated, due to outflow of soil during testing. Therefore it is assumed that the water absorption capacity of the soil in mix design C2.1 can be estimated by the values deducted from the results of mix design C1.4. This assumption is supported by the maximum theoretical absorption capacity of the soil, which equals 91.2 g when applied in 1L of pervious concrete with a void ratio of 23% and a soil water holding capacity of 40 vol-%.

The maximum water absorption capacity of mix design C2.1 in combination with coarse soil is 265.1 g/L. The evaporation rate for the conditions in the climate chamber is low and is equal to 9.1 g/L/day. This implies that it takes approximately 29 days before complete dry out of the substrate occurs. Rain is usually occurring at least once a month in the Dutch climate which would suggest that the moisture requirement can be fulfilled by implementing mix design C2.1 and coarse soil as the substrate layer. However, in reality this quick calculation is too simplistic. The evaporation rate is namely depended on the moisture content and complete dry out is not occurring in reality. The test results show that equilibrium conditions are reached after approximately 14 days. Furthermore, water losses due to higher temperatures, wind, sun radiation and transpiration of plants are not taken into account. Since the equilibrium conditions are reached within 14 days for climate chamber conditions, equilibrium ("dry out") will be reached even faster when those factors are taken into account. This implies that the moisture requirement is not fulfilled by the finishing layer. This conclusion is supported by the estimated water absorption capacity of the masonry finishing layer in the GreenQuays pilot project in Breda. The masonry finishing layer absorbed approximately 375 g/L, but could not successfully host quay wall plants without the addition of a capillary substrate layer. This indicates that the water absorption capacity of the finishing layer should at least be higher than 375 g/m^2. The water absorption capacity of the finishing layer made of mix design C2.1 and coarse soil is below this limit. This comparison confirms that this substrate layer is not fulfilling the moisture requirement. Therefore alterations are considered in the next chapter to improve the quay wall design.

Table 8.1: The water retention properties per L of finishing layer for mix design C2.1 and coarse soil

	Mix design C2.1	Coarse soil	Combination
Absorption after 24 hours [g/L]	62.4	108*	170.4
Absorption after 14 days [g/L]	98.7	87.9*	186.6
Maximum absorption capacity [g/L]	188.8	76.3*	265.1
Evaporation after 24 hours** [g/L]	4.8	4.3	9.1

* The absorption of the coarse soil decreases in time as the higher initial values are partly caused by faster water absorption in the pervious concrete due to the capillary effect in the soil in the pores.

** For T = 20 ± 2 °C & RH = 55 ± 5 %.

Mix design with pumice stone aggregate
A mix design with pumice stone aggregate in combination with a WCR of 0.4 and an ACR of 2 is not tested in the experimental part. However, the first series of testing suggests that replacing lava stone aggregate by pumice stone aggregate can increase the water absorption capacity by a factor of 2.5. When this factor is applied on the results of the second series, this leads to a water absorption capacity of 472 g/L for a mix design similar to C2.1 with pumice stone instead of lava stone. This is probably an overestimation as the cement content in the second series is higher, reducing the impact of the aggregate type.

The water absorption capacity of a 100 mm thick substrate layer made with pumice stone aggregate and filled with coarse substrate is expected to be slightly higher than the water absorption capacity of the masonry finishing layer of the left strip of the quay wall panel tested in Breda. This does not mean that establishment of vegetation is possible, but it shows that the water absorption capacity is slightly higher than the non successful left strip of the tested panel. As plants could also not survive on the thicker right strip it is suggested that increasing the thickness of the finishing layer does not help to improve the moisture availability. It also suggests that appropriate moisture conditions cannot be obtained on material level even if the finishing layer is further improved by changing the aggregate type. However, if sufficient capillary water absorption is possible in the substrate layer, this finishing layer might be suitable for vegetation without extra design alterations. In this case it might prove beneficial to increase the thickness of the finishing layer as the thickness of the capillary substrate layer is proven to be important (Mulder, 2022). Additional investigation on the moisture transport behaviour can clarify if sufficient capillary water transport is possible, which would make extra design alterations unnecessary.

8.1.2. Other ecological requirements
The acidity of the pervious concrete and the soil is not tested in the experimental part, but in chapter 4 it is concluded that no alterations to the pervious concrete mix designs are needed to fulfil the alkalinity

requirement. The natural carbonation process quickly reduces the pH level of pervious concrete to a suitable level as long as the interconnected porosity is sufficient. The nutrient availability is also not tested, as chapter 4 concluded that appropriate initial conditions can be obtained by appropriate soil selection. For this it is important that the interconnected porosity ratio is sufficient to ensure that soil can be added to the macro-pores. When vegetation is established in the starting phase, the circular environment provides nutrients to the vegetation. If vegetation has failed to establish in this first phase, accumulation of nutrients on the surface of the pervious concrete should ensure appropriate nutrient availability. The last two ecological requirements, which are the surface roughness and root ability, are also associated to the interconnected porosity as is explained in chapter 4.

Mix design with lava stone aggregate
Since the interconnected porosity of mix design C2.1 is above the requirement of 18% it can be assumed that the last four ecological requirements are fulfilled on material level. No extra alterations to the design are needed to obtain the correct conditions for the establishment of vegetation when mix design C2.1 is used for the pervious concrete layer except for alterations focused on increasing the water retention properties.

Mix design with pumice stone aggregate
The interconnected porosity of the mix design made with pumice stone is expected to be slightly lower than the similar mix design made with lava stone due to the difference in particle form. As the void ratio of mix design C2.1 is approximately 23%, it is expected that the margin is just enough to ensure that a similar mix design made with pumice stone will obtain the minimum void ratio of 18%. This implies that the last four ecological requirements can be fulfilled on material level when pumice stone is used as coarse aggregate material.

8.2. Technical requirements

The technical requirements are boundaries for the 28-day compressive strength and the freeze-thaw durability.

Mix design with lava stone aggregate
Mix design C2.1 fulfils the compressive strength requirement as the 28-day compressive strength of this mix design is 7.9 MPa with a standard deviation of 0.36 MPa. This mix design also fulfils the freeze-thaw durability requirement of less than 25% mass loss after 18 cycles as the mass loss is only 0.98% after 18 cycles with a standard deviation of 0.15%. No additional design adjustments are thus needed for the implementation of this mix design as pervious layer of a quay wall.

Mix design with pumice stone aggregate
The results of the first series show that the compressive strength of the mix designs made with pumice stone aggregate is lower compared to those made with lava stone aggregate. However, this can also be caused by the lower cement content in the samples with pumice stone. The results of the second series namely show that a higher cement content increases the compressive strength significantly. It is uncertain if the minimum compressive strength of 6 MPa can be reached by the altered mix design with pumice stone. As there is some margin between the minimum compressive strength and the 28-day compressive strength reached by mix design C2.1, the requirement is still reached if the strength is slightly lower due to the use of pumice stone aggregate. Additional testing is needed to determine the actual 28-day compressive strength for the mix design with pumice stone.

The freeze-thaw resistance of the mix design with pumice stone aggregate is predicted based on the results of the first and the second series. An extensive background of this prediction can be found in Appendix C. The estimated number of cycles after which the mass loss is equal to the limit of 25% is 19 cycles. This prediction indicates that it might be possible to reach the durability requirement for a mix design with pumice stone. To validate this and to determine the actual freeze-thaw resistance additional testing is recommended.

9
Water characteristics of the quay wall

In the design of the quay wall, techniques should be included that provide a constant moist environment for vegetation. Dry-out should be prevented (for a period longer than two weeks) over the whole height of the quay wall. A too wet quay wall is unlikely, due to evaporation and run off of abundant water. In chapter 8 it is determined that the tested mix design that fulfils the technical requirement cannot fulfil the moisture requirement on material level. It is recommended to investigate the capillary water absorption of a mix design with pumice stone aggregate, since a successful design can only be obtained on material level if the capillary water absorption is sufficient (0.9 m). Apart from recommending further research to pumice stone aggregate in pervious concrete, system modifications are considered in this chapter to improve the moisture availability. This is associated to sub-question 3:

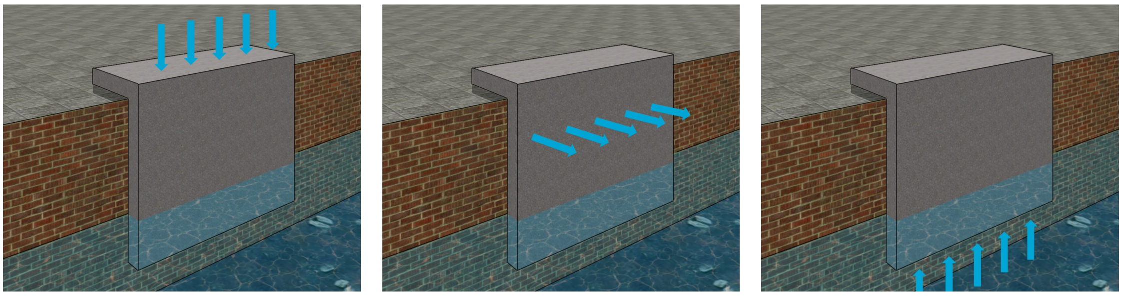
"How can the design of the quay wall be adjusted to improve the water characteristics of the system?"

To ensure a continuously moist environment both the income and outcome of water should be considered. For the inflow of water different solutions based on multiple water sources are considered. The potential they have for water supply is evaluated by literature research. The loss of water happens due to run off and evapotranspiration (evaporation and transpiration). If the rate of water replenishment is equal to the rate of evapotranspiration and run-off, the moisture content does not change, which is the desired situation.

9.1. Water sources

For designing the system modifications, understanding of the different water sources and associated challenges is needed. Different water sources are distinguished that can help to fulfil the moisture needs of the vegetation. Water can be transported from above, from behind and from below, as is illustrated in Figure 9.1. Rainwater falls directly on the quay wall or is transported to the quay wall via city surfaces. Water can also be supplied from behind, which resembles the traditional situation. Groundwater in the soil behind the quay wall construction should be transported to the vegetation to be able to utilize this source. The last water source is the water in the canal, which should be moved upwards to be able to moisturize the vegetation over the whole height of the quay wall.

Multiple system modifications exist that focus on the different types of sources. When using rainwater as a water source, direct runoff to the canal should be prevented. The amount of rainwater that is supplied is variable in time. During rainstorms a lot of water is supplied and the challenge is to retain the water, so it can be used during a dry period. Rainwater is partly retained by porous concrete, but the level of retention is unsatisfactory in dry periods. The retention of water on the quay wall is thus the challenge. Groundwater in the back layer soil is traditionally the source for vegetation on quay walls in dry periods, but installation of modern water-resistant quay wall constructions such as steel sheet piling, made this water inaccessible for vegetation on the quay wall. Transport through or around these water-resistant constructions forms the main challenge when you want to use this water source. The last water source that is mentioned is the water from the canal. This source offers good opportunities, but the transport of water against gravity is the point of issue in this case. Pros and cons to the use of



(a) Rainwater (b) Groundwater behind the quay wall (c) Canal water

Figure 9.1: Type of water sources which can be used to design a moisturized quay wall

the different water sources are mentioned in Table 9.1. Water in the air can also be viewed as a water source, which is done in the article by Pirouz et al. (2020) on fog water harvesting for green walls. It is not mentioned as a water source, since the use of water from air will result in a too complex outer system, which is not suitable as a quay wall. Furthermore, moisture absorption via the liquid phase is considerably faster than absorption via the vapor phase (Bakker and Roessink, 1990).

Table 9.1: Comparison of the three water sources on which design alterations should be based

	Rainwater	Groundwater	Canal water
Water availability	Sufficient (when adequate water storage on the quay wall)	Not sufficient (limited water passing through water-resistant layers)	Sufficient (when adequate capillary effect)
Reliability	Not reliable	Reliable	Reliable
Complexity system	Not complex, since water flow along quay wall is a natural process	Complex since coordinated alterations are needed for both water-resistant layers (the constructive layer and the steel sheet piling)	Complex due to additional materials needed for vertical water transport against gravity

The advantage of using rainwater over the other two sources is the fact that no extra water transport is required. Rainwater flow over the quay wall is a natural process that requires no additional design alterations. Despite this great benefit, the use of rainwater is unreliable. In long dry and hot periods, evaporation will most likely cause complete dehydration of the quay wall. The time before this happens can be extended by increasing the water retention capacity, but eventual dehydration is inevitable if no water is provided by precipitation.

History has shown that groundwater can deliver enough water for a sufficient moisture level all year round if the quay wall materials are water permeable. However, the water supply from behind is insufficient in modern constructions since steel sheet piling is not water permeable and alterations to the design of the steel sheet piling are limited by the structural function. The limit to the water permeable contact area will most likely result in underachievement of the moisture conditions.

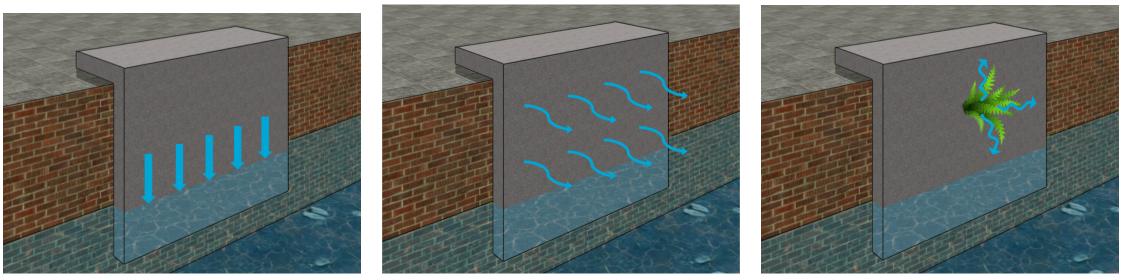
The potential of using canal water is high since this source is always available, as it is independent of the weather as long as the bottom side of the quay wall is in contact with the canal water. The canal is a practically inexhaustible source, so sufficient moisture supply should not be a problem. However, the vertical transport demands appropriate capillary action, which cannot be provided by the porous concrete, since the capillary effect of concrete with an average pore diameter greater than 1 millimeter is insignificant (Tang et al., 2022). Additional materials would thus be needed to overcome the height, which results in a more complex design.

9.2. Water loss

Water loss happens due to three different processes: run off, evaporation and transpiration. In Figure 9.2 all types of losses are visualised. The water that is lost due to gravity forces is considered as run off. This is most significant when the water supply is high during a rain storm, so more water is supplied than can be absorbed by the finishing layer. The water that cannot be absorbed directly flows to the canal.

Evaporation is the process where water changes from liquid to vapour. It occurs from open water surfaces, but also from materials that contain water. In the application of a pervious quay wall, water can be lost directly from the pervious concrete or from the soil which is located in the pores of the pervious concrete. Different factors influence the evaporation quantities. A large surface area is positively correlated to evaporation. The quay wall has a large surface area in proportion to its thickness, which means that evaporation has a great impact on the water that is stored in the substrate layer. Furthermore the parameters radiation, temperature, wind and moisture content increase the evaporation speed. Increased humidity, decreases the evaporation rate (Barghi, 2018).

The second process that effects the loss of water is transpiration. This process is associated with the presence of vegetation. The roots of the plants take up water, which is partly used for the growth and metabolism, but the major part is lost via stomatal cells, which are pores that can open. During opening water vapour is lost. Although the uptake of water through roots reduces the water availability in the substrate layer, vegetation also has a positive side effect. Vegetation namely causes shading of the surface from direct solar radiation, which reduces surface temperature, and vegetation decreases the wind speed. These factors influence the evaporation as described before, so vegetation is beneficial for the amount of water that is lost through evaporation (Barghi, 2018).



(a) Run off (b) Evaporation (c) Transpiration

Figure 9.2: Type of water losses

9.3. System modifications

Multiple system modifications are suggested for the design to overcome the previously mentioned challenges associated to the water sources. As the water availability of groundwater is not sufficient for modern quay walls and the system modifications are complex, it is concluded that solutions based on this source have the least potential of the three highlighted sources. Therefore system modifications focusing on this water source are disregarded. Rainwater is always used as a source independently of the system modifications due to the absorption capacity of the finishing layer. There are system modifications that can further improve the retention of rainwater to prevent direct flow to the canals. For the utilization of canal water system modifications are needed that include capillary materials and these modifications should thus be evaluated. The design modifications can also be directed towards the water losses to reduce the evaporation rate. To limit the scope, solutions that are focused on reducing evaporation are not part of this investigation.

9.3.1. Utilizing rainwater

For the solutions focusing on the utilization of rain water, it is most important that direct flow to the canal is prevented. Water should be retained, so it remains accessible for the vegetation on the quay wall.

This can be done at two locations, namely above the vertical part of the quay wall in the capping stone, so it can later be distributed over the quay wall or at the vertical part of the quay wall, where water can be retained so it is directly available for the vegetation.

Rainwater retention in capping stone
The capping stone is the horizontal part of the quay wall element. If there is enough space available, the capping stone can be made with an reservoir inside as is illustrated in Figure 9.3. By making the top surface with a water permeable pavement, rainwater flows into the reservoir from the city surfaces. The outflow from the reservoir can be regulated by another water permeable material. For designing the water permeable material, the k-value of those materials is important. The k-value, also known as the intrinsic permeability, is a measure of how easily a fluid can pass through a porous material. Porous materials with a high k-value tend to have a higher water permeability, meaning that water can flow through them more easily and quickly. Conversely, materials with a low k-value have a lower water permeability, so water is less likely to pass through them.

A reservoir in a capping stone is not encountered in previous research, but the idea of Barbara Standaert of a rainwater collecting bench consisting of a pervious concrete cover and a watertight concrete reservoir, shows some similarities to the capping stone reservoir. The design functions as a bench, a planter and a rainwater tank and has won the Henry van de Velde Award 2020 ("A rainwater collecting bench made with porous concrete - MaterialDistrict", 2019). This example shows that the design of a reservoir for watering of vegetation is most likely possible. However, it showed that care should be taken for including a water overflow and expansion space for freezing water when designing a water reservoir with watertight concrete and porous materials.

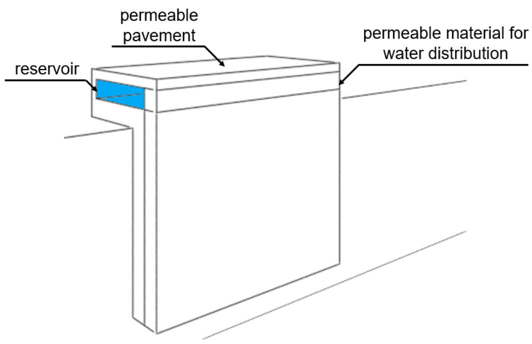
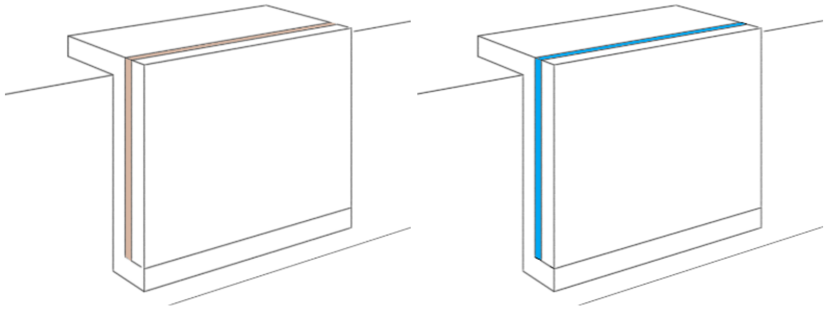


Figure 9.3: Visualisation of a quay wall element with a reservoir in the capping stone for rainwater retention

Rainwater retention in vertical part of the quay wall
The rainwater is partly retained by the pervious concrete and the soil inserted in the macro-pores of the pervious concrete. Part II of this thesis focused on that aspect of the water retention. Additional layers can be added to increase water retention on the vertical part of the quay wall. For this a cavity is made between the structural layer and the finishing layer. The cavity can be filled with a material with high water absorption as is visualised in Figure 9.4a or the cavity can be used as a water reservoir as is illustrated in Figure 9.4b.

Filling the cavity with a highly water retaining material is a good solution, but it is best to focus on materials that have appropriate capillary working. In that case the material in the cavity can retain both rain and canal water. This alternative is thus reviewed in the following paragraph. Creating a reservoir in the vertical part of the quay wall comes with a lot of drawbacks. The porosity of the pervious concrete layer has to be gradated to make it less permeable at the side of the reservoir to prevent fast outflow of the water from the cavity. Additionally, freeze-thaw durability will most likely be a problem as water in the cavity expands when frozen and creating expansion space is difficult in this design. This can cause failure of the pervious layer during FT cycles. Both solutions are not included in the MCA due to the obvious drawbacks and limitations.



(a) Highly water retaining material in cavity (b) Water reservoir in cavity

Figure 9.4: Visualisation of a quay wall element with with rainwater retention in the vertical part

9.3.2. Utilizing canal water

To utilize the canal water, water should be transported vertically against gravity forces. The system should not use any mechanical devices to overcome the height differences and the most promising solutions are thus based of the capillarity of materials. To chose appropriate capillary materials, understanding of this topic is required. First, the capillary rise in capillary vessels is discussed, followed by the capillary rise in concrete. Lastly, the capillary rise in soils and similar materials is discussed.

Capillary rise in capillary vessels

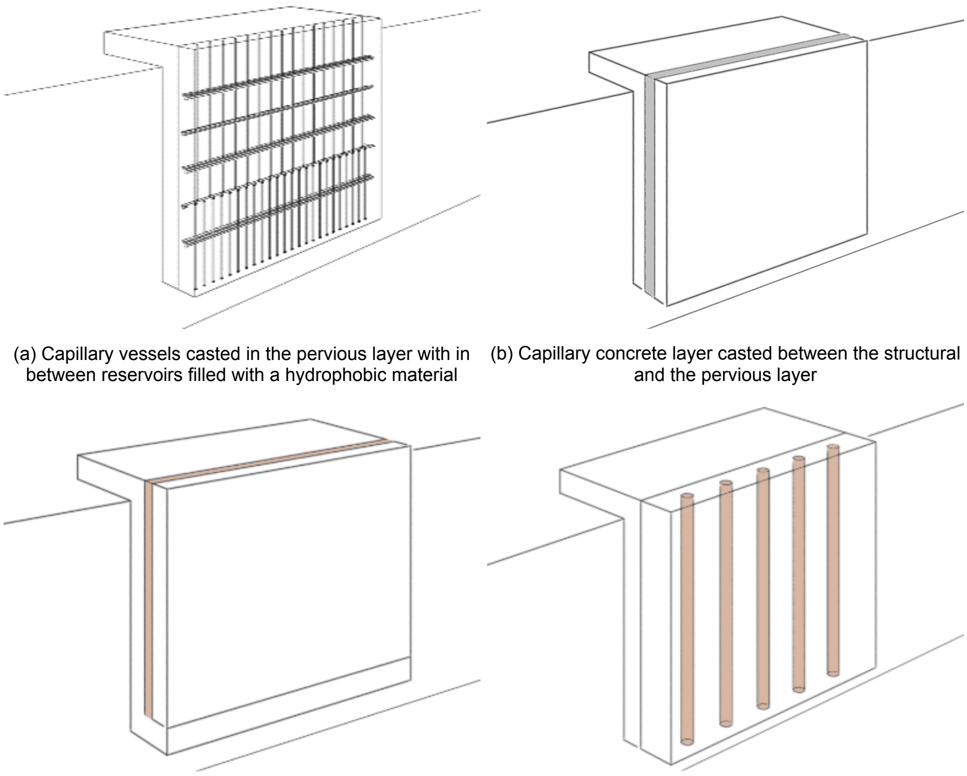
Capillarity is the ability of a liquid to flow inside narrow spaces against gravity and without the assistance of external forces. Water molecules near the sides of capillaries are pulled upward due to adhesion forces and cohesion forces keep the water molecules together causing all water molecules to follow the upward lift. This phenomenon is a passive form of water transport. The capillary effect is described by the capillary rise rate, maximum capillary height and the volume of water that is drawn upwards.

The capillary rise height increases with a decreasing diameter of the capillary, but the capillary rise rate and the water volume decreases. The parameters should therefore be balanced to find an optimal for the design of a product which can transport enough water to the top, so water replenishment is high enough to compensate for water loss at all height levels. The capillary rise height of a liquid in a capillary vessel is given by equation 9.1 and is thus depended on the liquid vapour surface tension (γ_{LV}), the contact angle(θ), the density of the transported fluid (ρ), the gravity constant (g) and the capillary radius (r) (Barghi, 2018).

$$h = \frac{2\gamma_{LV} \cos\theta}{\rho g r} \tag{9.1}$$

The capillary radius that enables a capillary rise height of 2 meters can be found with equation 9.1 with the assumption that the contact angle is equal to zero since the equilibrium should be reached at a height of 2 meters. The following values are taken for the other constants:
$\rho = 997\ kg/m^3$, $g = 9{,}8\ m/s^2$, and $\gamma_{LV} = 72.8 * 10^{-3}\ N/m$. The radius of $7\ \mu m$ which is found through the equation 9.1 is a theoretical value and is only valid in perfect capillary vessels. However, the capillary materials that will be discussed further on, do not have perfect capillary vessels, so the optimal radius of the pores and the voids of these materials deviates from the theoretical value.

In the paper by Dangwal and Aggarwal (2019) the idea of water transport by using capillaries instead of a motor or pump, is discussed for irrigation purposes. Multiple bunched capillary tubes are proposed to lift the water over a certain height. Extraction of the water at the higher end is the main problem as it will not drain out on its own. For this purpose, sponge cotton, carbon fibre or some super hydrophobic material is used at the delivery end. Once the water is stored in a higher reservoir the process can be repeated any number of times for lifting it further to the desired elevation. The concept as described is not tried before, but seems feasible. Based on this concept a design including capillary vessels to vertically transport canal water is proposed. The radius of the capillary vessel that reaches a height of 2 meters is small, resulting in a low capillary rise rate and capillary rise volume. Therefore, the design uses capillary vessels with increased diameters and lower rise heights. By including in between reservoirs containing water absorbing materials to extract the water from the capillary tubes, an elevation of 2 meters can be obtained. A visualisation of this design is given in Figure 9.5a. As the production of this solution is technically complicated and the used concept is untested, this option is not included in the MCA.



(a) Capillary vessels casted in the pervious layer with in between reservoirs filled with a hydrophobic material

(b) Capillary concrete layer casted between the structural and the pervious layer

(c) Capillary material in cavity

(d) Capillary material in vertical hollow tubes

Figure 9.5: Visualisation of the considered system modifications for vertical transport of canal water

Capillary rise in concrete

Pervious concrete is unsuitable for vertical water transport, since the capillary effect of concrete with an average pore diameter greater than 1 millimeter is insignificant (Tang et al., 2022). Instead this section focuses on the possibility of adding an extra concrete layer, which is adapted to maximize the capillary rise height. A visualisation of this system modification is included in Figure 9.5b

The theoretical limit of capillary rise in concrete is in the order of magnitudes of kilometers. However, in practice this limit is restricted by the capillary rise rate, which is slower than the evaporation rate at a certain height. The water transport in concrete is quite complex and strongly depends on the microscopic pore structure, concrete surface, dynamic effects, pore size distribution, moisture content, temperature, external environment and water pressure. In previous research on concrete specimens with a height of 5 centimeter the equilibrium is reached after 2 to 3 months (Wei et al., 2013. Another experiment on concrete samples with a height of 16 centimeter concluded that a capillary rise height of 14 centimeters is reached after 12 months for the mix design with the highest capillary rise (Zhang et al., 2022). These experimental findings indicate that the capillary rise rate in ordinary concrete is low and will not reach the 2 meter requirement. This option is thus disregarded.

Capillary rise in alternative material
The capillary rise effect is seen in soils, since the voids between soil particles form capillary vessels. The height of capillary rise which is reached in a soil is a function of time until the equilibrium has settled. The time until a constant value is reached, depends on the soil material. In a coarse-grained soil the equilibrium is reached in less than 10 days, but for a fine-grained soil this can take up to 400 days. This difference is associated to the capillary rise rate, which is depended on the diameter of the capillary vessels. Small particle size soils create narrower void spaces which results in finer capillary vessels than bigger particle size soils. Narrow vessels positively influence the maximum capillary rise height but negatively effect the other parameters that describe capillarity (capillary rate and moisture volume). Pores with a radius smaller than 0.1 μm are too small, causing extremely slow water movement, which practically does not contribute to the capillary transport. The constituents of the soil should be carefully chosen to obtain appropriate capillary rise rate and height. (Lubelli, 2022)

Capillary soils can be incorporated in the design by creating a cavity between the structural layer and the finishing layer, which is filled with substrate as is done in the reference projects of vegetated masonry quay walls in paragraph 2.1.1. A visualisation of this design is shown in Figure 9.5c. The quay wall project in Delft showed that a substrate layer of 110 mm thickness is better for survival of plants than a layer of 55 mm. Therefore a thickness of 100 mm for the cavity is chosen for this system modification.

The design including a cavity is especially suitable for masonry quay walls, as the two layers are produced separately, so creation of a cavity between the two layers is simple. However, for two-layered pervious concrete the creation of a cavity complicates the production. The pervious layer is casted on top of the structural layer, which ensures a proper connection between the two layers. When a cavity has to be created, a different production method is required, which makes the pervious layer an exterior system which is not integrated with the structural part of the quay wall. To prevent the separate production of the two layers, integration of the capillary soils is vertical tubes in the pervious layer is considered. This results in the design visualised in Figure 9.5d. The tubes can only be included in the pervious layer, if this layer is made thick enough to make sure that the pervious concrete has sufficient strength in the thin weak spots around the tubes. Furthermore, the casting process might become more complicated as hollow spaces should be made to be able to create vertical tubes. This is a conceptual design, but the experimental part showed that the compressive strength requirement is hardly reached by the pervious concrete mix designs. Increased strength to assure a stable system despite of the excavations is probably not possible. This means that additional materials should be added to increase the strength of the pervious layer, which makes the design more expensive and less sustainable. The design is included in the MCA in the next chapter, but the expectation is that it will have a low score. The design including capillary material in a cavity is also included in the MCA, despite of the drawback for the production process. For both designs the use of BVB substrate is recommended, as this substrate type can reach a capillary rise height of 1.5 meters as is proven in the pilot project in the Houthaven in Amsterdam. BVB substrate has a maximum water holding capacity of 40 vol-% (Denters et al., 2019).

9.4. Multi criteria analysis
In the previous paragraph multiple system modifications are proposed to improve the water retention characteristics of a quay wall element. In this paragraph a multi-criteria analysis (MCA) is performed to do a systematic assessment to compare the previously mentioned system modifications. The goal is to rank these modifications, to eventually design and model the highest ranked system modification in the next chapter. Background information on the procedure of the performed MCA can be found in Appendix D. The procedure consists of seven steps, which are discussed below.

9.4.1. Problem analysis
The problem analysis is done in the previous part of this thesis, resulting in the following short description of the goal: *"Improving the water retention properties of the layered vegetated pervious concrete element to make a self-sustaining quay wall"*. The modification of the mix design of pervious concrete that are investigated in this research cannot enhance the water retention properties sufficiently. Therefore, system modifications should be implemented to further improve these properties. The possible system modifications are used to define the options analysed with this MCA. The problem is a ranking

problem and the ranking is used to determine which system modification is used in the final design variant which is modelled in the next chapter.

The simple additive weighting method is chosen as technique for performing the MCA. It is a straightforward model that attempts to calculate the overall performance of the different options for all the criteria, but it must be noted that this technique might lead to inconsistencies and errors (Dean, 2022). Therefore a well-considered selection of the criteria is important and the weighing and scoring procedures should be chosen with care. To prevent the error that the objectives and criteria are selected based merely on the previously identified options, a ”value-focused thinking” approach is chosen. This approach determines the objectives, criteria and weights before identifying the possible solutions. In practice, it is a continuing process of interaction, where the criteria, weights and alternatives influence each other.

9.4.2. Objectives and criteria

The objectives are based on the four general goals of this investigation which can be found in Table 9.2. The associated criteria are included in this table as well. Not all goals are equally important. The primary goal is already discussed and focuses on improving the water retention properties by applying system modifications to stimulate the growth of vegetation. The other three goals are subordinate to the primary goal, which is presented by the weight factors per criterion.

The water storage objective is associated to the primary goal. Modern day quay wall constructions are not suitable for vegetation, since the quay wall is not in direct contact with the soil water due to water retaining constructions. Improving the water characteristics of the quay wall can ensure that the inability of the quay wall to extract water from the soil layer behind the quay wall is not limiting the vegetation. The following four criteria are associated to the primary goal: the water capacity, the water loss and replenishment speed and the dependency of the water storage on rainfall or manual replenishment.

Although the enhancement of the moisture retention properties is strongly related to the establishment of plants, a separate objective is used to evaluate if the design alternative is able to emulate the biodiversity value of the old historical quay walls. The growth of plants is namely also depended on the pH-value, the nutrient availability, the surface roughness and the interconnected porosity as explained in chapter 3.1. The effect of the system modifications on those properties should be accounted for as well. Furthermore, other types of organisms can also play an important role for the biodiversity of the quay wall. This objective is therefore split in a criterion that focuses on the additional properties important for the targeted vegetation and a criterion that focuses on the other forms of organisms that are stimulated by the quay wall design.

A secondary goal of this investigation is that the design should be producible and should have market-value. This is divided in two objectives. The first is concerning the technical feasibility of the design and the second is concerning the economic feasibility. The technical feasibility focuses on the technology itself and the possibility of the application of that technology in a quay wall. The corresponding criteria are the physical boundaries of the design, the technology readiness level, the production complexity and the end-of-life options. The economic feasibility focuses on the costs from the production, the material costs and the environmental costs.

Furthermore, the durability of the design is assessed with the fifth and last objective. The durability criterion focuses on the predicted life time and on the robustness of the system.

9.4.3. Weighting the criteria

A non-compensatory weighing technique is chosen to value the objectives. Since numerical information is not available, the ranking system is chosen. With this technique the objectives are ranked in order of importance. This is done by individually comparing each objective (Table 9.3). A score can be assigned to each objective based on the number of times the objective is more important than another objective. This score is distributed over the sub-criteria based on own judgement, resulting in the weights in Table 9.4.

Table 9.2: Criteria identification by establishing the goals and objectives which result in sub-objectives/criteria

General Goals	Specific Objectives	Sub-Objectives / Criteria
To stimulate the growth of plants by improving the moisture retention properties	[1] Water Storage	[1a] Water retention capacity [1b] Water loss speed [1c] Water replenishment speed [1d] Dependency on rainfall or manual replenishment
To emulate the biodiversity value of the old historical quay walls to be able to replace these walls	[2] Biodiversity value	[2a] Type and amount of targeted species and other vegetation [2b] Type and amount of other organisms
To be able to produce a design with market-value	[3] Technical feasibility	[3a] Physical boundaries [3b] Technology readiness level [3c] Production complexity [3d] End-of-life options
	[4] Economic feasibility	[4a] Production costs [4b] Material costs [4c] Environmental costs
To be able to reach the required life time	[5] Durability	[5a] Predicted life time

Table 9.3: Comparing importance of the main objectives

	[1]	[2]	[3]	[4]	[5]	Score
[1]	-	>	>	>	>	5
[2]	<	-	=	>	>	3.5
[3]	<	=	-	>	>	3.5
[4]	<	<	<	-	<	1
[5]	<	<	<	>	-	2

[1] = Water storage, [2] = Biodiversity value, [3] = Technical feasibility, [4] = Economic feasibility, [5] = Durability

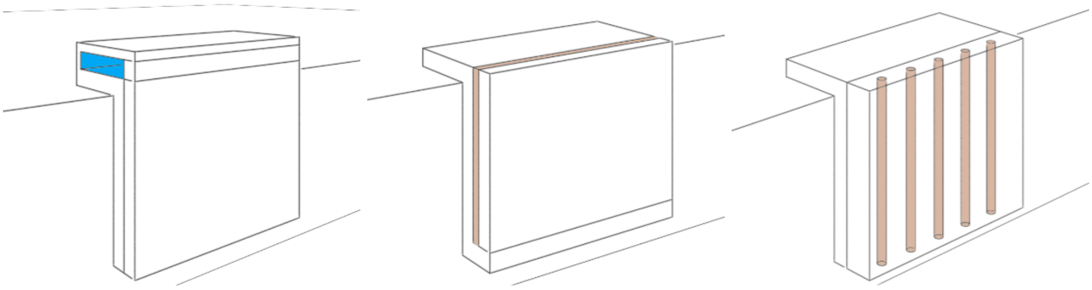
‘<’ criterion at the left is less important than criterion at the top, ‘=’ criterion at the left is equally important as criterion at the top, ‘>’ criterion at left is more important than criterion at the top

9.4.4. Options

The options to be assessed are designed based on the primary goal. All options are intended to reach this goal to a certain extent. In chapter 8 different design alternatives are discussed. Some of the options are already disregarded as it is known on forehand that the technique is not suitable to reach the primary goal to a certain extent. An option is also disregarded if the option has to many obvious drawbacks to reduce the number of options included in the MCA for simplification of the MCA. The three options that remain and are considered are visualised in Figure 9.6. All options focus on decreasing the dependency on rainfall and manual replenishment (one of the criteria) by utilizing a water source that is also available when it is not raining. The first two options are derived from techniques that are already in use in a similar application, but the implementation of the technology in combination with pervious concrete is new. The third option is derived from the second option, but is adapted to prevent the need for separate production of the two layers as this nullifies the benefits of the use of pervious concrete in this application.

9.4.5. Performance profile

The performance profile is based on assumptions and predictions, since no experiments are conducted on the system modifications. The performance profile is thus limited to the information that is available in this stadium of the research. The performance profile can be found in Appendix D.



(a) Option 1: Reservoir in capping stone (b) Option 2: Capillary substrate in cavity (c) Option 3: Capillary substrate in tubes

Figure 9.6: The options that are assessed with the MCA

9.4.6. Scoring

When scoring the options per criteria, the factors from Appendix D are taken into account. The knowledge on the performance of the alternatives is limited to the information in the performance profile, therefore a narrow Likert-type scale from 1 to 5 is chosen. The performance scores are included in Table 9.4.

Table 9.4: Scoring and ranking of the options

		Option 1		Option 2		Option 3	
	Weight factor	Score	Weighted score	Score	Weighted score	Score	Weighted score
[1a]	0.133	4	0.533	5	0.667	4	0.533
[1b]	0.033	2	0.067	5	0.167	5	0.167
[1c]	0.033	5	0.167	4	0.133	3	0.100
[1d]	0.133	2	0.267	5	0.667	4	0.533
[2a]	0.167	4	0.667	1	0.167	2	0.333
[2b]	0.067	1	0.067	1	0.067	1	0.067
[3a]	0.067	4	0.267	1	0.067	1	0.067
[3b]	0.033	4	0.133	4	0.133	1	0.033
[3c]	0.100	4	0.400	1	0.100	3	0.300
[3d]	0.033	2	0.067	4	0.133	2	0.067
[4a]	0.033	5	0.167	1	0.033	3	0.100
[4b]	0.033	4	0.133	2	0.067	4	0.133
[4c]	0.067	2	0.133	4	0.267	2	0.133
[5a]	0.067	2	0.133	5	0.333	5	0.333
Total score			**3.200**		**3.000**		**2.900**
Rank			**1**		**2**		**3**

9.4.7. Rank

In Table 9.4 the options are ranked according to the total score of each option. The corresponding total scores are included in the table. Option 1 which is the system modification with a water reservoir in the capping stone is the alternative with the highest score and thus the first ranking position.

10
Design Variant

The MCA in chapter 9 showed the potential of the design variant of a two-layered pervious concrete quay wall with a reservoir in the capping stone. In this chapter the water flows for this design variant are modelled in Python to determine if this design can fulfil the moisture requirement dictated by the vegetation.

10.1. Design and assumptions

The design of the quay wall is visualised in Figure 10.1. The pervious concrete layer is made according to mix design C2.1 from part II as this is the only mix design that fulfils the compressive strength demand. The macro-pores of the pervious concrete are filled with coarse soil, since the results of the coarse soil are better than those of the fine soil. The finishing layer made of pervious concrete and coarse soil is referred to as the substrate layer. Mix design C2.1 is not tested with the inclusion of soil. Therefore the effect of the coarse soil mixture on the water absorption and retention of the substrate layer is deducted from the test results of series C1.4 with and without coarse soil.

The tests of part II are performed in a climate chamber at a constant temperature and with a con-

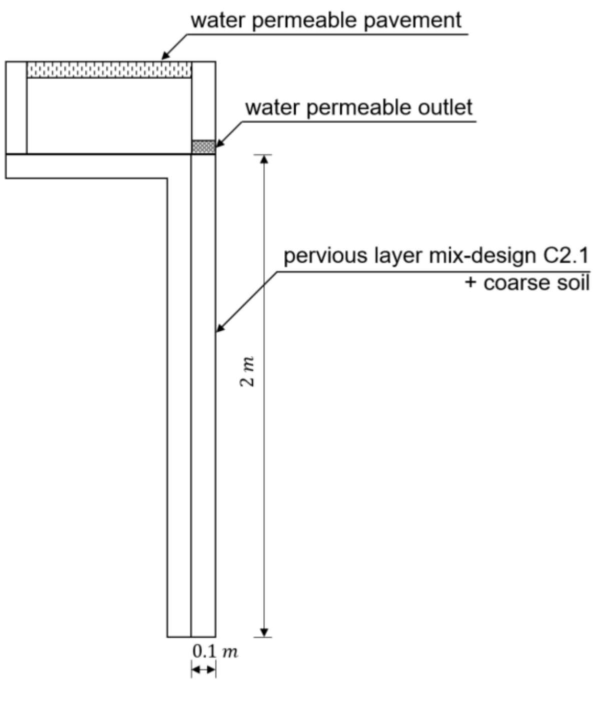


Figure 10.1: Design of the quay wall

stant relative humidity. For the first scenario the climate chamber conditions are considered for the evaporation rate. However, in reality the weather conditions differ from the conditions in the climate chamber which effects the evaporation rate. For the second scenario the evaporation data of the Royal Netherlands Meteorological Institute (KNMI) is therefore used instead of the measured evaporation in the climate chamber. For both scenarios the precipitation data of the KNMI is used to determine the inflow of the model.

The evaporation data is calculated by the KNMI according to the method of Makkink which requires the incoming shortwave radiation and the mean daily temperature. The method determines the reference crop evapotranspiration per day, which includes evaporation from the soil and transpiration by the vegetation. The reference crop type is grass, so the evapotranspiration data is the amount of water that is lost from a soil grown with grass. To convert the reference crop evapotranspiration to values specifically applicable for certain crop types, crop factors are used. As no crop factors are defined for the selected wall species, the evapotranspiration rate is approached by the reference evaporation rate in the second scenario. In the Netherlands, the method of Makkink accurately approaches the evapotranspiration rate during the growing season. Outside the growing season this method is overestimating the losses due to evapotranspiration. As the winter months are not critical for the moisture availability for the vegetation, the evapotranspiration rate in this period is less important for the design. Therefore the values according to Makkink are used throughout the whole year in the second variant.

The inflow and outflow from the reservoir and the substrate layer are visualised in Figure 10.2. For the calculations, the following assumptions are used to model the reservoir:

- The width of the reservoir is 0.5 m, which is important for the evaporation rate from the reservoir.
- Rain water that falls on a city surface area of 4 m^2/m flows into the reservoir.
- The inflow of rainwater is not restricted by the water permeable pavement.
- The evaporation rate from the reservoir is equal to the evapotranspiration rates calculated by the KNMI.
- The effect of water pressure on the outflow of the reservoir is ignored. A constant outflow rate is assumed as long as there is water in the reservoir.

The following assumptions are used for modelling the water content of the substrate layer:

- The height of the vertical part of the quay wall is 2 meters.
- The thickness of the substrate layer is 100 mm.
- Water outflow from the reservoir is equally distributed over the substrate layer.
- The precipitation directly on the wall is determined with an angle of incidence of 5°.
- Capillary water absorption from the canal is ignored.
- Water absorption and evaporation are independent of the moisture content of the substrate layer .
- The maximum water absorption of the substrate layer within 24 hours is based on the water absorption in the first 24 hours in the experiments in part II.
- The maximum water absorption capacity of the substrate layer is based on the water absorption capacity after 14 days in the experiments in part II.
- The water evaporation from the substrate layer within 24 hours for the first scenario is based on the water evaporation in the first 24 hours of the experiment in part II.

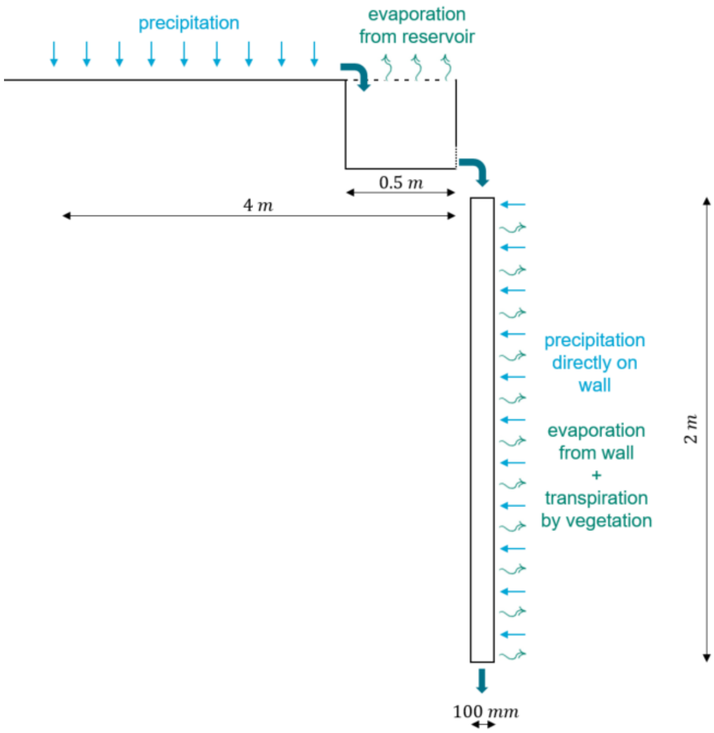


Figure 10.2: Inflows and outflows of the reservoir and the substrate layer

10.2. Modelling the reservoir

10.2.1. Inflow and outflow

The addition of the reservoir is most important for the moisture supply during the critical period, which is the period during which the vegetation is suffering as the moisture availability is limited. The design of the reservoir should thus be based on this period to assure that the moisture content of the substrate layer is improved during this period. The k-value should be within a certain range to assure that too fast emptying of the reservoir does not occur, but sufficient water supply to the substrate layer is guaranteed. An appropriate k-value for the outflow of the reservoir is determined by balancing the average inflow and outflow during the critical period. This means that the water level in the reservoir is (on average) constant, which is the desired situation as this means that the reservoir is not emptied during a critical period.

The pictures in Appendix E show that the most difficult period for the vegetation on a quay wall is the period from June to August, due to high evaporation rates and low precipitation rates. Therefore this period is chosen to determine the k-value of the outlet. The inflow due to precipitation is based in the precipitation measurements of the KNMI. As no data is available on the water evaporation from a water reservoir with a water permeable pavement cover, the evapotranspiration data of the KNMI is used. For open water evaporation, the Makkink reference crop evaporation is multiplied with a factor of 1.25 (Droogers, 2009). Since the reservoir is covered, the evaporation rate is probably lower, so a factor of 1.0 is used instead of a factor of 1.25. The data from June to August over the period from 2018 to 2022 from the weather station in Rotterdam is analysed. The average evaporation and precipitation rates are given in Table 10.1, which results in a final average evapotranspiration of 3.4 mm/m^2/day and a final average precipitation of 2.4 mm/m^2/day. Combining this with the assumption that an area of 4m^2/m contributes to the inflow due to precipitation and that an area of 0.5m^2/m contributes to the outflow due to evaporation, this means that the outflow from the reservoir to the substrate layer should be 7.9 L/day/m to balance the flows. When equally distributed over the substrate layer, this results in 39.5 g/day per liter of substrate.

Table 10.1: The average precipitation and evaporation in the period from 1st of June till the 31nd of August

	Precipitation [mm/m^2]	Evaporation [mm/m^2]
2018	1.9	3.6
2019	2.5	3.4
2020	3.1	3.2
2021	2.4	3.0
2022	2.1	3.6
AVG	2.4	3.4

10.2.2. Results and interpretation

In practice, the precipitation and evaporation are fluctuating, so the water level in the reservoir is not constant. The previously mentioned data from the KNMI is used to more accurately predict the water volume in the reservoir for the past 5 years. Appendix F.1 shows the results of the volume in the reservoir over time for a reservoir with a volume of 0.2 m^3/m and a k-value of 7.9 L/day/m (type a). These graphs show that the reservoir is emptied quite often for long periods. The assumed k-value for the outlet is thus not leading to a reservoir that can constantly deliver water to the substrate layer. In 2018 the reservoir would have been empty for more than a month in the period from June to August as can be seen in Figure 10.3. Some dry periods are also seen during April and May, which is catastrophic for the vegetation as this is during the growing season. To ensure that the reservoir is emptied less often, the k-value of the outlet can be reduced. Another option is to increase the volume of the reservoir. To determine the effect of the adjustments, the reservoir volume is modelled for two different types of reservoirs, namely one reservoir with a k-value of 5.0 L/day/m instead of 7.9 L/day/m (type b) and one reservoir with a volume of 0.3 m^3/m instead of 0.2 m^3/m (type c). Both adjustments can only slightly improve the water retention volume in the reservoir during long periods of drought as is visible in Appendix F.1. Therefore both alterations are combined for the calculation of a variant with a reservoir volume of 0.3 m^3/m and a k-value of 5 L/day/m (type d). The water content in the pervious concrete is thus calculated for a reservoir volume of 0.2 m^3/m in combination with a k-value of 7.9 L/day/m and for a reservoir volume of 0.3 m^3/m in combination with a k-value of 5.0 L/day/m.

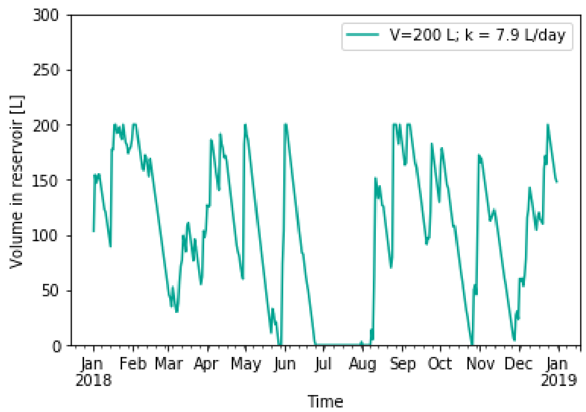


Figure 10.3: Water volume in reservoir in the year 2018 for V = 200 L/m and k = 7.9 L/day/m

10.3. Modelling the substrate layer

10.3.1. Inflow and outflow

The water inflow and outflow of the substrate layer is modelled to determine the moisture content of the substrate layer over time. The inflow of water is depended on two sources as is illustrated in Figure 10.2: the water flowing from the reservoir to the substrate layer and direct precipitation on the wall. The reservoir is not delivering water to the substrate layer if the reservoir is empty. Therefore the water volume in the reservoir, which is modelled in the previous paragraph, is needed to determine the inflows.

Furthermore, the outflow from the substrate layer is depended on evaporation, transpiration and run-off. It is assumed that run-off only occurs if the inflow is higher than the maximum 24h water absorption or when the maximum water absorption capacity of the substrate layer is reached (Table 10.2).

The losses due to evaporation and transpiration are considered in different scenarios. The first scenario is the scenario where the conditions from the climate chamber apply. In the climate chamber the temperature is kept constant at a level of 20 ± 2 °C and the relative humidity is kept constant at a level of 55 ± 5 %. The water evaporation from the substrate layer is determined based on the experimental part of this thesis. The water evaporation in the first 24 hours of the measurement is used to determine the water evaporation per day. In reality the evaporation rate is depended on the moisture content, so the use of the evaporation rate of the first 24 hours is overestimating the evaporation rate for lower moisture contents. In this scenario, the losses due to transpiration and wind are not considered. As this scenario is not an accurate representation of reality, a second scenario is considered. In this scenario the data of the KNMI is used as the evaporation rate per day. This data resembles the actual conditions better, by taking into account the measured incoming shortwave radiation and the mean daily temperature of the past 5 years. The evapotranspiration rate is assumed independent of the moisture content. In reality the evapotranspiration rate is lower if the moisture content is lower. As the data of the KNMI is based on the situation where enough water is available, the losses due to evapotranspiration are overestimated.

The water content is modelled for the design with reservoir type a, which is a reservoir with a volume of 200 L/m and a k-value of 7.9 L/day/m (variant 2a) and for reservoir type d, which is a reservoir with a volume of 300 L/m and a k-value of 5.0 L/day/m (variant 2b). For comparison the water content in the substrate layer for the design without reservoir is also modelled (variant 1). In this variant the reservoir is removed from the model, so rain water that falls on a city surface of 4 m^2/m flows directly to the substrate layer. precipitation of a city surface of 4 m/m is directly flowing to the substrate layer.

Table 10.2: Properties of the substrate layer determined with the results of part II and discussed in chapter 8 for modelling the water content in the substrate layer

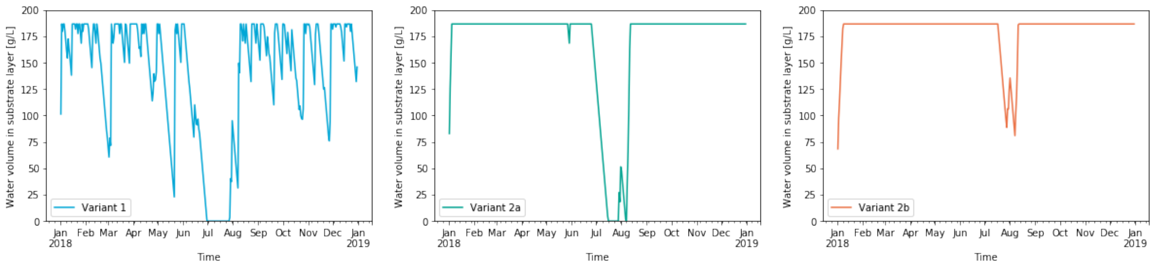
	Substrate layer
Maximum absorption 24h [g/L]	170.4
Maximum absorption 14d [g/L]	186.7
Evaporation 24h [g/L]	9.1

10.3.2. Results and interpretation

Scenario 1: Conditions as in climate chamber

The results for the first scenario are included in Appendix F.2.1. The effect of the addition of the reservoir is clearly visible in Figure 10.4. The moisture content of the substrate layer is highly fluctuating when the reservoir is not included (variant 1), while the moisture content is more constant with some troughs (during long dry periods) when a reservoir is included (variant 2a and 2b). Without a reservoir, the moisture content is equal to zero for a period of approximately one month in 2018 even without the inclusion of transpiration by vegetation. During the other years the dry-out of the substrate layer does not exceed the limit of two weeks even without a reservoir as can be seen in Table 10.3. For the variant with a reservoir with a volume of 300 L/m and a k-value of 5.0 L/day/m the moisture content of the substrate layer is never equal to zero. The variant with a reservoir with a volume of 200 L/m combined with a k-value of 7.9 L/day/m leads to a moisture content that is only shortly reaching zero (< two weeks).

The modelled moisture content for the variants with a reservoir for climate chamber conditions is promising as the requirement for the moisture content is fulfilled. The substrate layer is namely not dry for a period longer than 2 weeks for both reservoir types. The performance of the design variant without reservoir is slightly worse, but the dry period exceeds the two week limit only once in 5 years. As the moisture requirement is not a strict requirement and the limit is exceeded only once, it is expected that the selected species can successfully develop for climate chamber conditions without the addition of a



(a) Design variant 1 (b) Design variant 2a (c) Design variant 2b

Figure 10.4: Modelled water volume in the substrate layer in the year 2018 for scenario 1 (T = 20 ± 2 °C & RH = 55 ± 5 %)

Table 10.3: Duration of dry period for scenario 1

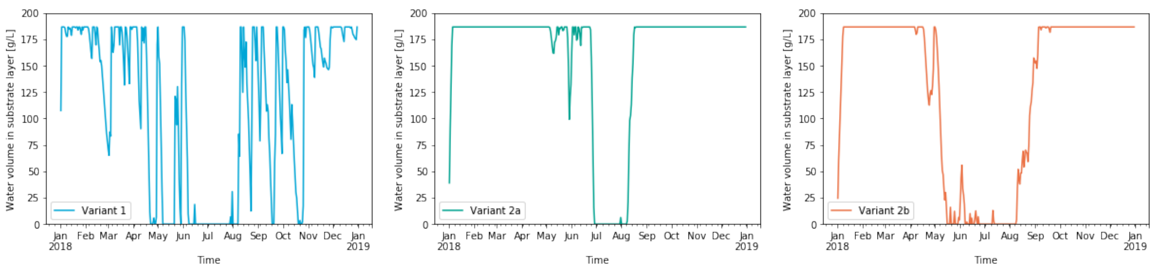
Variant	Duration of dry period >1 week	>2 weeks	>4 weeks	>6 weeks
1	3	1	1	0
2a	1	0	0	0
2b	0	0	0	0

reservoir. This suggests that the addition of a reservoir is undesired as it is not critical for development of ecologically valued species, but does increase the material use.

However, the conditions in the climate chamber do not resemble the actual situation as the temperature and the relative humidity are not constant, but deviate from the climate chamber conditions. In the first scenario water losses due to transpiration by vegetation are not considered. Furthermore, increased evaporation due to wind and sunlight is not taken into account in this scenario. To include those factors, the evapotranspiration data of the KNMI is used instead of the evaporation data from the experiments in the second scenario. The final recommendations for the design are thus based on the second scenario.

10.3.3. Scenario 2: Evaporation according to measurements of the KNMI

The moisture content of the substrate layer is modelled for the three design variants based on the second scenario. The graphs for the period from 2018 to 2022 can be found in Appendix F.2. The length of the dry periods is determined and an overview is given in Table 10.4. Contrary to the results of the first scenario, the reservoir with a higher k-value performed better than the reservoir with a lower k-value. The can be explained by the high evaporation rate in the second scenario. When the evaporation rate is higher than the water inflow from the reservoir, the moisture content decreases or stays equal to zero despite of the water supplied by the reservoir. This principle is occurring when the k-value is equal to 5.0 L/day/m. When a reservoir is implemented in the design the k-value of the water permeable outlet should thus be higher than 5.0 L/day/m. Similarly to the first scenario the moisture content of the substrate layer is highly fluctuating when no reservoir is included (variant 1).



(a) Design variant 1 (b) Design variant 2a (c) Design variant 2b

Figure 10.5: Modelled water volume in the substrate layer in the year 2018 for scenario 2 (T = 20 ± 2 °C & RH = 55 ± 5 %)

Table 10.4: Duration of dry period for scenario 2

Variant	Duration of dry period >1 week	>2 weeks	>4 weeks	>6 weeks
1	23	10	1	1
2a	7	4	1	0
2b	14	5	1	0

The design with a reservoir volume of 200 L/m and a k-value of 7.9 L/day/m exceeds the two week limit only four times in five years of which once for more than four weeks. This indicates that enough moisture is available for the vegetation most of the time. There will be some critical periods, but the quay wall can probably host the selected species to a certain extent. To improve moisture characteristics, minimal maintenance could be implemented during the critical periods. Increasing the volume of the reservoir can also be considered to create a more stable environment for the vegetation. However, the increase of the size of the reservoir has a minimal impact due to the high evaporation rates utilized for the reservoir. These rates are based on the evapotranspiration data of the KNMI. The factor used to determine the open water evaporation from the reference crop evapotranspiration is already reduced from 1.25 to 1.0, as the reservoir is covered and thus not directly exposed to wind and sunlight. It is unknown if this reduction is sufficient. When the actual evaporation rates from the reservoir are lower, the increase of the volume of the reservoir has a greater impact.

Without a reservoir, dry out of the substrate layer for more than two weeks is occurring ten times in five years, from which one time for more than six weeks. Due to the number of dry periods and the extensive length of one of the dry periods, the changes for vegetation are less promising for the design without a reservoir. Maintenance can be implemented, but without a reservoir these measures are only shortly effecting the moisture content of the quay wall.

10.4. Discussion

A lot of assumptions are needed to model the reservoir and the substrate layer. First of all the effect of the soil is derived from the results of mix design C1.4 with and without soil, but mix design C2.1 is applied as the pervious layer. As the macro-porosity of this mix design is lower, less soil can be added to the pores, resulting in a lower water absorption capacity. Since outflow of the soil is observed during testing, it is assumed that the overestimation of the amount of soil in 1 L of pervious concrete is minimal. Additional testing needs to be done on mix design C2.1 in combination with soil to check if this assumption is correct.

In equilibrium conditions, the pervious concrete contains water, so complete drying of the sample as is modelled is not happening in reality. If the effect of the moisture content on the evaporation rate is taken into account, the minimum moisture content is automatically higher than zero. When this is included in the model, the moisture requirement has to be adapted as complete dry out will never occur. The limit for dry out should be increased to the equilibrium conditions of the pervious concrete in the climate chamber. As the effect of the moisture content on the evaporation rate is neglected, the limit for dry out is not adjusted to the equilibrium conditions.

The maximum water absorption per day is based on a completely dry sample. A dry sample absorbs more water than a sample with a higher moisture content and the water absorption per day is thus an overestimation. The maximum water absorption capacity and the maximum water absorption per day are based on the tests where one side of the sample is in contact with water. In reality the water is flowing through the sample due to gravitational forces. The effect of this different method for water supply has to be investigated to accurately determine the maximum water absorption capacity (per day). The water absorption will probably be higher, because of the flow of water through the sample. This ensures that the overestimation due to the too high maximum water absorption per day is less notable.

The capillary water absorption is ignored. However, the experiments where the cube is immersed in a small layer of water showed that capillary suction is occurring especially in the samples including soil. The substrate layer at the lower part of the quay wall will thus be wetter due to the capillary effect. The water that flows from the reservoir is equally distributed over the quay wall in the model. In reality, more water is distributed over the upper part of the substrate layer. If you combine the previously described factors, this still results in an approximately even distribution over the substrate layer, but the quantity of water inflow would be higher. Assuming an equal distribution is thus no problem for the model, but the inflow of water due to capillary water absorption should be accounted for to improve the model.

10.5. Conclusion

Modelling the substrate layer for conditions similar to the climate chamber showed that mix design C2.1 in combination with coarse soil can host the ecologically preferred species to a certain extent even without the addition of a reservoir. As the actual water losses are higher due to increased temperatures, wind, sunlight and transpiration by vegetation, an extra model is made based on the evapotranspiration data of the KNMI. This model showed that lowering the k-value from 7.9 L/day/m to 5.0 L/day/m negatively effects the moisture content of the substrate layer. The k-value of the water permeable outlet of the reservoir should thus be between 5.0 and 7.9 L/day/m. The volume of the reservoir should be at 200 L/m or higher.

The moisture requirement for the quay wall is not fulfilled for the design variant with a reservoir volume of 200 L/m and a k-value of 7.9 L/day/m. Increasing the volume of the reservoir can improve the design variant for the moisture requirement, but within a logical boundary for the reservoir volume, the moisture requirement is not fulfilled for the second scenario. As the water evaporation from the reservoir is probably overestimated, it is perhaps possible to make a design variant with a reservoir and a substrate layer that can fulfil the moisture requirement. This should be checked by more extensive testing to make a less simplified model and by determining the water evaporation from the reservoir more accurately.

Discussion

This research consists of several parts utilizing different methodologies. For the first part, literature research is used to obtain the information on the ecological requirements, technical requirements and the material properties (related to the requirements). The second part, which is the experimental part, makes use of the Taguchi method and the full factorial design method on different scales. In the third part, a multi-criteria analysis is used to compare the proposed system modifications. The most promising solution is modelled based on the in- and outflow of water from the reservoir and the substrate layer. This section discusses the methodologies that are used in this thesis and provides a description of the limitations of these methodologies.

Part I
Although the final goal of designing a vegetated quay wall can be the hosting of protected species threatened to extinct, a more feasible goal for the early design stages is the hosting of ecologically valued species. Protected species are currently rarely seen on traditional quay walls, while ecologically valued species do occur on traditional quay walls. This more feasible goal has a higher probability of success and makes it possible to use historical data of traditional quay walls to create the framework for the design. Once the design is successfully hosting ecologically valued species, the goal can be expanded to protected species and the framework can be adjusted accordingly.

A list of preferred vascular plant species is determined based on ecological articles on the type of vegetation seen on quay walls in Dutch cities. This selection is validated with qualitative data of the organization ”Floron”. Furthermore, the plant should also be categorized as a wall plant according to the Dutch Red List to be regarded as a ecologically valued specie. Determining which plant species are ecological valued species on Dutch quay walls based on the previous information is not done before as the focus is usually on protected species. This is thus a valuable addition to current literature as the list of ecologically valued species can be used for quay wall replacement projects.

The method for selecting ecologically valued species is depended on the availability of articles on quay wall plants in Dutch cities. The articles from different cities are combined to determine general information for quay wall environments in the Netherlands. The differences between cities are not accounted for. Specific orientation and location are also not included. When the location of implementation is known beforehand, it is best to analyze the quay wall ecology of that (or a similar) location. Furthermore, the investigation is limited to five ecological requirements. In reality, additional factors such as temperature, light and availability of seeds influence the process of establishment of plants. These factors are indirectly taken into account by the selected plant species, but when the location of implementation of the quay wall is known, this should be included at the start of the design process.

Three of the five ecological requirements (moisture availability, alkalinity and nutrient availability) are determined making use of the Ellenberg values of the selected species. Those values normally apply to the soil in which a plant grows, but in this investigation these values are used for the finishing layer made of pervious concrete. Utilization of the Ellenberg values for this different type of substrate should be validated with planting tests. As the moisture availability, alkalinity and nutrient availability are based on the selected species, the selection is crucial for the eventual design. To reduce the possible error that might occur from inappropriate selection of species, general information on the wall characteristics of traditional quay walls is utilized for the formation of the ecological requirements.

Part II
The Taguchi method is used in the experimental part to reduce the number of samples. In hindsight, it would have been better to reduce the number of parameters and use the full factorial design method instead of the Taguchi method. The use of the Taguchi method namely complicates the analysis and benefits are not obtained as the levels chosen for the third parameter are unsuitable for determining the

effect of that parameter. Furthermore, the aggregate type parameter is a qualitative parameter. Therefore, changing this parameter varies the water absorption of the aggregate as well as the particle form and the surface roughness, resulting in a low internal validity. The variation of a qualitative parameter should therefore not be combined with the variation of other parameters.

The effect of the aggregate type on the water absorption capacity is in correspondence with the hypothesis. Utilization of an aggregate with high water absorption is beneficial for the water absorption capacity of the pervious concrete. Unlike the hypothesis, increasing the water absorption capacity by changing the aggregate type is also possible for a WCR of 0.4. This can be explained by the fact that the permeability of the cement paste is also sufficient for a WCR of 0.4 due to the thickness of the cement paste layer. Although an aggregate type with high water absorption can improve the water absorption capacity, the freeze-thaw resistance is reduced which is in accordance with literature.

The effect of a parameter is only invested within the predetermined boundaries. The range for the WCR is from 0.4 to 0.8. As a decrease in the WCR is clearly beneficial for the compressive strength of the pervious concrete and a WCR of 0.4 is still appropriate for producing pervious concrete which is able to absorb water in the aggregate material, it might be interesting to invest a WCR below 0.4 if the strength requirement is limiting the mix design. The number of aggregate types invested in this research is also limit, but as the aggregate type is a qualitative parameter, the internal validity of the results is low. Prediction of the properties of pervious concrete made with a third type of aggregate cannot be determined with sufficient accuracy. Before implementing an aggregate type which is not included in this investigation, extensive testing should be done to validate its strength and durability properties.

Part III

Inclusion of all options during a design process is impossible as the process is depended on the ideas of the designer. Furthermore, not all ideas are suitable or achievable. The development of the system modifications is focused on the water flow to the quay wall to assure a more constant inflow. Adaption of modern-day technologies consisting of water-resistant layers is not considered during this investigation as this would broaden the topic too much. Therefore groundwater in the soil layer behind the quay wall cannot be utilized to assure moisture availability. Furthermore, the options do not focus on minimization of the water losses. The third part shows that the evaporation losses are considerable, indicating that the potential of this design strategy could be high. For a more complete assessment, the previously excluded solution directions should be included in follow-up research.

An MCA is used to compare the three most promising system modifications. It is attempted to make a fair comparison by evaluating the performance of the three system modifications for certain criteria. However, scoring of the options is based on assumptions and value judgement, as the design is still in the exploratory phase. Therefore the analysis is subjective. Further developing the design variants, can improve the level of detail of the MCA as the scoring can be based on qualitative data instead of assumptions.

The experiments of the second part are conducted for climate chamber conditions, so a constant temperature and relative humidity are considered (T = 20 ± 2 °C, RH = 55 ± 5 %). The effect of additional factors such as wind, radiation and transpiration are not included in the results. As this leads to an inaccurate representation of reality, the evaporation rates determined by testing cannot be utilized for accurate prediction of the moisture losses of the substrate layer. The evapotranspiration rate calculated by the KNMI based on incoming shortwave radiation and the mean daily temperature, does include those factors and is used for better predictions. However, this data does not include material properties of the substrate layer, as it assumes a soil grown with grass for the reference evapotranspiration values. The vertical orientation, the type of vegetation, the pervious concrete in the substrate layer and the dependence of the evapotranspiration on the moisture content of the substrate layer are thus not accounted for in the evapotranspiration rate.

Conclusion

This research aims to design a quay wall with a finishing layer made of pervious concrete to promote establishment of vegetation on modern day quay walls. This thesis therefore focused on the following research question:

"How can the build-up and mix design of the layered concrete element, with the focus on the substrate layer, be optimized to obtain a self-sustaining quay wall system that imitates the ecological function of a traditional masonry quay wall in a freshwater canal of a Dutch city whilst fulfilling the technical requirements?"

In order to answer this research question, the three sub-questions are answered, which can be combined to finally answer the main research question.

Sub question 1
"Which type of vascular plant species are specific for the ecosystem on a traditional masonry quay wall and what (wall) characteristics allow the growth of those ecologically valued species?"

A list of vascular plat species is conducted based on the ecosystem that is currently seen on traditional quay walls. The selected plants are not endangered species, but these are species that might suffer from endangerment when traditional quay walls are replaced with modern day construction technologies. The following five factors are crucial for establishment and development of wall plants: moisture, alkalinity, nutrients, surface roughness and root ability. The first three factors are specie specific, so the ecological requirements associated to those factors are based on the Ellenberg values of the selected species. The last two requirements are based on experiences with plant growth on (pervious) concrete.

The requirements are obtained in traditional masonry quay walls due to degradation of bricks and mortar. Degradation reduces the pH-value and increases the surface roughness of the building materials. Increased surface roughness is important for accumulation of seeds, but also for accumulation of nutrients. When the surface roughness is thus appropriate, the nutrient demand is also fulfilled over time. Furthermore, crack formation due to degradation provides space for roots. Moisture is provided by the groundwater in the soil layer behind the wall and can be transported to the plants due to increased porosity of the masonry wall as a result of degradation. Reference projects indicate moisture availability as the most challenging requirement, due to the water impermeable construction technologies in modern-day quay walls.

Sub question 2
"How can the pervious concrete mix design be adjusted to control the previously indicated characteristics on material level?"

Literature research shows that most of the requirements can be obtained on material level by using an appropriate mix designs for pervious concrete. Water retention in pervious concrete is not included in former research and is therefore investigated in the experimental part of this research. This proves that water retention is possible when using lava stone aggregates in combination with a WCR of 0.4 and an ACR of approximately 2 whilst fulfilling the strength and durability demands. The 28-day compressive strength is 7.9 MPa and the mass loss after 28 FT cycles is only 2-8%. Furthermore, an appropriate void ratio of 23% is obtained, which is (indirectly) associated to the four ecological requirements. To enhance moisture retention in the substrate layer, soil should be added to the macro-pores of pervious concrete. Although water retention is possible whilst fulfilling the other ecological and technical requirements, appropriate moisture availability is not reached on material level by implementing the proposed mix design in combination with a soil mixture.

It should be validated if pumice stone aggregate can be used to (partly) replace lava stone aggregate to increase the water absorption capacity of the finishing layer. However, even if this is possible, the water absorption capacity of the substrate layer is probably not (significantly) higher than that of the masonry finishing layer in the reference project in Breda. Without the addition of a capillary substrate layer the masonry finishing layer in Breda was not successful for hosting plants. This reference project also showed that increasing the thickness of the finishing layer could not improve the development of vegetation on the quay wall. This suggests that the moisture requirement cannot be fulfilled on material level except if appropriate capillary rise is reached in the substrate layer. Extensive testing should determine the maximum capillary rise height of pervious concrete in combination with a soil mixture. If a capillary rise height of 1 meter is not reached, additional design alterations need to be considered to further improve moisture availability in the quay wall. As all other requirements are fulfilled by the substrate layer, those requirements do not have to be considered for the design alterations.

Sub question 3

"How can the design of the quay wall be adjusted to improve the water characteristics of the system?"

Since the answer of sub question 2 showed that the moisture requirement is only reached on material level when sufficient capillary rise in the substrate layer is proven, different system modifications are considered for improving the water characteristics of the whole system. The MCA shows that implementing a water reservoir in the capping stone is currently the option with the most potential. The model made of this design variant shows that the k-value of the water permeable outlet should be between 5.0 and 7.9 L/day/m. The reservoir volume should be at least 200 L/m. Water is available most of the year, but dry out of the substrate layer occasionally exceeds the two week limit. This means that the moisture requirement is not fulfilled without intermediate manual irrigation, suggesting that the quay wall is not suitable for hosting ecologically valued species. However, the moisture requirement is not a strict requirement, so the current design will presumably be able to host the ecologically valued species to a certain extent. Compared to the reference project in Breda, the moisture properties are not improved as the finishing layer containing lava stone aggregate and coarse soil can absorb less water than the masonry finishing layer. The dependence on rainfall is slightly reduced due to the addition of a water reservoir. Increasing the volume of the reservoir can be considered to create a more stable environment for the vegetation, but this has limited impact due to the high evaporation rates that causes fast emptying of the reservoir. A minimum form of maintenance should probably be implemented to improve the moisture conditions in the substrate layer during long dry periods. The reservoir is increasing the length of the impact of manual irrigation, which is a benefit of the design with a reservoir. If proven possible, the water absorption capacity of the substrate layer from the current design could be improved by (partial) replacement of lava stone aggregate with pumice stone aggregate.

The inflow-outflow model for the second scenario should be improved to validate if the moisture content in the substrate layer of the design variant with reservoir is appropriate for the ecologically valued species. Factors such as capillary water absorption and accurate evaporation based on the moisture content of the substrate layer should be taken into account. The improved model could also be used to determine the potential of the design variant without a reservoir made with a mix design where lava stone aggregate is (partially) replaced by pumice stone aggregate.

Final conclusion

Literature research shows that appropriate conditions can be obtained for establishment of vegetation on pervious concrete in an irrigated situation. Literature concerning the topic of self-sustaining pervious concrete is not available, so this thesis is the first exploration in the implementation of pervious concrete in quay walls. Therefore no definitive conclusions can be made. Nevertheless, the first exploration showed that the use of lava stone aggregate material is recommended for its water retention properties. The use of other lightweight aggregate materials with better water absorption properties should be further investigated to determine if those types of aggregates can also be implemented whilst fulfilling the strength and durability demands. Partial replacement of lava stone aggregate could enhance the water absorption if the strength and durability demands are not met for complete replacement. The use of a WCR higher than 0.6 is not recommended as it only slightly increases the maximum water absorption capacity, whilst the negative consequences for the strength and durability are significant. The addition of a soil mixture to the macro-pores of pervious concrete is recommended as it significantly increases the maximum water absorption capacity. Furthermore, the capillary effect in the substrate layer is increased when soil is added. The addition of a water reservoir in the capping stone is recommended as it improves the water availability in the substrate layer when an appropriate k-value is chosen. The current model suggests that the quay wall can host ecologically valued species to a certain extent, but some critical dry periods will occur during its lifetime. To improve the water characteristics a minimum for of maintenance can be implemented. An improved inflow-outflow model, could prove that that such a form of maintenance is unnecessary.

Recommendations

This research is an exploration in the design of a quay wall with a pervious concrete finishing layer. It shows some possibilities, but as it is still a new topic, more research is required. In this section recommendations for further research are included.

Substrate layer
Especially the substrate layer is an interesting subject for future research as this is a relatively new type of material and research is lacking for pervious concrete in combination with a soil mixture. First of all, experiments with vegetation are not included in this research due to time limitations. Instead the ecological requirements are used to create appropriate conditions for the preferred vegetation. As these requirements are eventually highly simplified by (indirectly) linking four of the five requirements to the macro-porosity of the pervious concrete, experiments should validate this simplification. It should thus be determined if the selected species can indeed grow on the substrate layer if the minimum void ratio is obtained in pervious concrete. The experiments including vegetation should in first instance be done in an irrigated situation to assure that the moisture conditions are not limiting the vegetation.

It is concluded that the mix design that fulfils the strength and durability requirements, cannot fulfil the moisture requirement of the vegetation when implemented as finishing layer of a quay wall in combination with a soil mixture without other design alterations. The model including the water reservoir in the capping stone showed some improvement of the moisture content of the substrate layer over time. Presumably, the preferred species can grow on that design to a certain extent, but it is believed that improving the water retention capacity of the substrate layer can further optimize the design. Therefore research on pervious concrete made with other aggregate types such as pumice stone would be a valuable addition to the current knowledge. It should be determined if the water absorption capacity can be improved by changing the aggregate type whilst fulfilling the strength and durability requirements when the WCR is equal to 0.4 and the ACR is around 2.

The addition of a soil mixture to the macro-pores of the pervious concrete is only tested for one mix design of the first series of pervious concrete. This research should thus be extended to include the mix-designs that fulfil the strength and durability requirement. As the macro-porosity of the mix design that fulfils the technical requirements differs from the mix designs tested in combination with the soil mixture, the effect of the addition of the soil mixture might differ. Furthermore, the effect of the implementation of a soil mixture on the strength and durability properties should be investigated. Additionally, the capillary rise height, rate and volume in the substrate layer should be quantified by testing. As some outflow of the soil mixture from the macro-pores is observed during the experiments in this research, the method for applying the soil mixture to the pervious concrete should be improved. Preliminary testing showed that improvements can most likely be obtained by reducing the time for vacuum suction. More experiments should validate this preliminary finding, but if outflow cannot sufficiently be prevented in the current set up, the water absorption testing methods should be adjusted to prevent outflow during the experiment.

Quay wall design
The simple design variant with a substrate layer made of pumice stone aggregate is a promising alternative if a minimum capillary rise height of 1.0 meter is reached in the substrate. The thickness of the design should possibly be increased to assure appropriate moisture availability for the vegetation. The nominal thickness of the capillary substrate layer and the finishing layer in the reference projects is namely more than 100 mm. If the pervious substrate layer can fulfil both functions, it is likely that the thickness of the layer should be increased for proper functioning regarding the moisture absorption. Quay wall elements with various thicknesses of the substrate layer should be tested in actual situations before implementation of the quay wall on a larger scale is possible. Both the simple design variant and the design variant with reservoir should be included in the testing set up to validate if the

addition of a reservoir results in the expected benefits. Before experiments on such a large set-up can be conducted, it should be checked if pervious concrete made with pumice stone fulfils the technical requirements on material level.

The system modifications that are considered in this investigation focus solely on the water sources to ensure a more constant water supply to the substrate layer. However, as the evapotranspiration rates of the KNMI show that the water losses from vegetated soil are relatively high, high losses are expected for the substrate layer. Reduction of the losses by minimizing the evaporation rate is therefore an interesting solution strategy. Considering alternatives that can reduce those losses of the substrate layer could be a valuable addition to current literature. Furthermore, the groundwater in the soil layer behind the quay wall is not considered in this investigation. However, if modern day quay wall technologies are adapted, this source can play an important role for providing moisture to the vegetation. It is probably not viable to completely change modern day technologies solely for this purpose, but if the construction technology changes for different reasons, the vegetated quay wall design should be reconsidered.

Quay wall model

For modelling the design variants more accurately, additional measurements are needed. Water evaporation from the reservoir should be measured for conditions that resemble the actual situation where stagnant water is covered by a water permeable pavement in a Dutch climate. This can be done by simulating different combinations of factors in a climate closet and measuring the water evaporation rate from a bucket of water covered with permeable pavement. Combining the results with temperature, humidity and wind measurements of the KNMI can help to predict water evaporation in an outside environment.

The same type of measurements can be performed on pervious concrete including a soil mixture. When those results are available, the model should be improved so it takes into account the effect of the moisture content, wind, temperature and relative humidity on the evaporation rates. When the moisture content is accounted for, the equilibrium is automatically adjusted to the actual level instead of the theoretical complete dry out that is currently used. Furthermore, experiments should invest the capillary water absorption properties of the substrate layer, so this water source can be added to the model.

A

Appendix: Vicat measurements

Two vicat devices are used to determine the initial and final setting time of the cement paste mixtures. The settings of the devices are checked and are completely the same. However, the penetration depth curves show that the penetration depth of one of the devices is always higher and does never reach the penetration depth associated with the final setting time. As this difference between the results of those two devices is repeatedly seen as is shown in Figure 6.1, it is believed that something is wrong with the settings or the calibration of the second device, which is the one where the measurements do not reach the final setting depth of 2.5 mm.

P/REF and P/0.4 tested with the first Vicat (referred to as Vicat 1) reach the penetration depth of 2.5 mm associated to the final setting. The complete results can be found in Table A.3 and Table A.4. P/REF and P/0.4 tested with the second Vicat (referred to as Vicat 2) do not reach the final setting depth. The results of Vicat 1 are analysed to be able to determine the adapted final penetration depth for the samples tested with Vicat 2.

For P/REF and P/0.4 Vicat 1 reaches the final penetration depth of 2.5 mm after 9.71h and 9.85h, respectively. In the measurements after that the penetration depth the minimum penetration depth that is reached is 2.0 mm for both samples. The difference between the minimum penetration depth and the final setting depth is thus 0.5 mm. As this is the case for both samples it is assumed that this relation also occurs for the samples tested with Vicat 2. With this assumption the final setting depth can be determined from the minimum penetration depth reached during testing. This results in a final setting depth of $4.2 + 0.5 = 4.7$ mm and $4.1 + 0.5 = 4.6$ mm for Vicat 2, associated to the final setting times of 9.85h and 9.76h for P/REF and P/0.4, respectively. Those values are included in Table A.2. The method can only be used if it is certain that the final setting is reached within the testing time.

For P/0.6 and P/0.8 both Vicat 1 and Vicat 2 do not reach the final penetration depth as the shrinkage due to the high WCR is lowering the surface level and increasing the penetration depths. Determining the penetration associated with the final setting for both mix designs is based on the same relation that is previously found between the final setting depth and the minimum penetration depth. Again this relation may only be used when it is certain that the final setting is reached within the testing time. The results for the final penetration depths and associated final setting times for Vicat 1 are given in Table A.1.

Table A.1: Determining the final setting time of the samples tested with Vicat 1

Sample ID	Min. PD [mm]	PD final setting [mm]	Final setting time [h]
P/REF/1	2	2.5	9.71
P/0.4/1	2	2.5	9.45
P/0.6/1	2.9	3.4*	15.9
P/0.6/3	2.6	3.1*	15.73
P/0.8/1	4.6	5.1*	29.15
P/0.8/3	4.4	4.9*	29.83

* Adjusted penetration depth associated to the final setting based on the minimum penetration depth + 0.5 mm

Table A.2: Determining the final setting time of the samples tested with Vicat 2

Sample ID	Min. PD [mm]	PD final setting [mm]	Final setting time [h]
P/REF/2	4.2	4.7*	9.85
P/0.4/2	4.1	4.6*	9.76
P/0.6/2	5.2	5.7*	16.4
P/0.6/4	5.2	5.7*	17.88
P/0.8/2	7.7	8.2*	24.71
P/0.8/4	6.8	7.3*	26.59

* Adjusted penetration depth associated to the final setting based on the minimum penetration depth + 0.5 mm

Table A.3: Results of the setting time test obtained with the two Vicat devices for P/REF/1 and P/REF/2 (PD = penetration depth)

P/REF/1	Vicat 1	P/REF/2	Vicat 2
Time [h]	PD [mm]	Time [h]	PD [mm]
5.38	40	5.35	40
5.55	40	5.51	39.9
5.71	39	5.68	35.3
5.88	21.8	5.85	24.5
6.05	16.5	6.01	16.4
6.21	9	6.18	13.6
6.38	8.2	6.35	11.5
6.71	7.1	6.51	11.1
7.05	6.4	6.68	10.1
7.38	5.3	6.85	9.6
7.71	4.8	7.01	8.9
8.05	4.6	7.18	8.4
8.38	3.7	7.51	7.5
8.71	3.5	7.85	6.9
9.05	3.5	8.18	7.9
9.38	3.1	8.51	5.9
9.71	2.4	8.85	5.2
9.80	2	9.18	4.7
9.88	1.8	9.51	4.7
9.96	1.8	9.85	4.6
10.05	2.4	10.18	4.6
10.13	2.4	10.51	4.6
10.21	3.1	10.85	4.7
10.30	2.9	11.18	4.8
10.38	2.9	11.51	4.8
10.46	3.3	11.85	4.8
10.55	3.3	12.18	4.9
10.63	2.4	12.51	4.7
10.71	2.2	12.85	4.3
10.80	2	13.18	4.3
10.88	2	13.51	4.3
10.96	2.4	13.85	4.3
11.05	2.6	14.18	4.5
11.13	3.1	14.51	4.6
11.21	3.1	14.85	4.6
11.30	2.9	15.18	4.8
11.38	2.6	15.51	4.6
11.46	2.4	15.85	4.2
11.55	2.2	16.18	4.2
11.63	2.2	16.51	4.4
11.71	2.9	16.85	4.5
11.80	2.9	17.18	4.6
11.88	2.4	17.51	4.5
11.96	2.4	17.85	4.3

Table A.4: Results of the setting time test obtained with the two Vicat devices for P/0.4/1 and P/0.4/2 (PD = penetration depth)

P/0.4/1	Vicat 1	P/0.4/2	Vicat 2
Time [h]	PD [mm]	Time [h]	PD [mm]
4.28	40	4.26	40
4.45	40	4.43	40
4.61	40	4.60	40
4.78	40	4.76	40
4.95	40	4.93	40
5.11	40	5.10	39.9
5.28	39.7	5.26	39.3
5.45	28.9	5.43	34
5.61	17.2	5.60	31.1
5.78	14.3	5.76	19.4
5.95	10.6	5.93	19.6
6.11	7.7	6.10	12
6.45	5.1	6.26	10.7
6.78	4	6.43	9.3
7.11	3.5	6.60	8.6
7.45	3.5	6.76	8
7.78	3.3	7.10	6.7
8.11	3.1	7.43	6.1
8.45	2.9	7.76	5.7
8.78	2.6	8.10	5.4
9.11	2.6	8.43	5.3
9.45	2.4	8.76	5.2
9.53	2.2	9.10	4.9
9.61	2	9.43	4.7
9.70	2.6	9.76	4.4
9.78	2.4	10.10	4.3
9.86	2.6	10.43	4.3
9.95	2.6	10.76	4.4
10.03	2.4	11.10	4.1
10.11	2.2	11.43	4.1
10.20	2.2	11.76	4.3
10.28	2.4	12.10	4.4
10.36	2.2	12.43	4.5
10.45	2.2	12.76	4.3
10.53	2.2	13.10	4.2
10.61	2.6	13.43	4.1
10.70	2.4	13.76	4.2
10.78	2.2	14.10	4.1
10.86	2.2	14.43	4.2
10.95	2	14.76	4.3
11.03	2.4	15.10	4.3
11.11	2.2	15.43	4.1
11.20	2.2	15.76	4.2
11.28	2.4	16.10	4.2

B

Appendix: Error in the mix designs of the first series

The starting point of this research is the mix design proposed by Holcim Group in Lyon, containing lava stone aggregate, cement, water and a superplasticizer. As discussed in paragraph 5.3.1, some adjustments to this mix design are needed to obtain the mix designs for the first series of pervious concrete. In the first series some mix designs are namely made with pumice stone aggregate instead of lava stone aggregate. The dry particle density is needed to transform the dry aggregate weight in order to keep the ACR constant. Furthermore, in the original recipe dry aggregate is used with supplementary water to account for the water absorption by the aggregate in the concrete mixture. As pre-wetted aggregates are used in this investigation, the water absorption of the raw aggregates is needed to predict the amount of water absorbed when pre-wetting the aggregates. As the pervious concrete mix designs for the first series of pervious concrete are casted before the pyknometer tests are finished, the results for the dry particle density and the water absorption of the aggregates could not be used to adjust the mix design. Assumptions had to be made for both values for both types of aggregate.

B.1. Assumptions

Assumptions for the dry particle density

The dry particle density of the lava stone aggregate is provided in the original recipe from Holcim Group Lyon and is 2580 kg/m^3 for the fraction 4/16 mm. The dry particle density of pumice stone is not provided by the supplier and is calculated with equation B.1. The underwater weight of pumice stone is provided by H&B Grondstoffen and is 287 kg/m^3, resulting in a dry particle density of 1287 kg/m^3.

$$dry\ particle\ density = under\ water\ weight + density\ of\ water \tag{B.1}$$

Assumption for the 24h water absorption

The water absorption of the aggregates after 24 hours is assumed as 6.5% and 68% for lava stone aggregate and pumice stone aggregate, respectively. These values are based on a quick tests, where dried aggregate material is weighted and put in a bucket with water. After a day the aggregate material is surface died and weighted. The aggregate fractions are not sieved before testing. Lava stone is supplied in the fraction 8/16 mm and the quick test is performed on this fraction. The initially provided aggregate fraction of pumice stone is unknown. The quick test for estimation of the water absorption is thus performed on an unknown fraction. From observation it is concluded that the fraction is smaller than 8/16 mm.

B.2. Test results

Density according to pyknometer test

The dry particle density for lava stone from the recipe of Holcim Group Lyon is in accordance with the result obtained with the pyknometer test as can be seen in Table B.1. The dry particle density of pumice stone found with testing is 870.4 kg/m^3, which is not in accordance with the estimated value. As it is observed that the dry pumice stone aggregate material is floating on water, it is logical that the dry particle density is below 1000 kg/m^3, indicating that the estimated value of 1287 kg/m^3 is incorrect. This is in accordance with the fact that this value is outside the range for the dry particle density of pumice stone (700 - 1200 kg/m^3) provided by Group (2015). The result of 870.4 kg/m^3 falls within this range and has a low standard deviation implicating that this result is reliable. That an incorrect value is obtained with the calculation using the under water weight can be explained by two things. Firstly, the underwater weight that is provided by H&B Grondstoffen at the beginning of this investigation is incorrect. The underwater weight in the product folder is adjusted to a value of 100 kg/m^3. In this new product folder it is also clearly mentioned that this value is the saturated underwater weight, something that is not mentioned in the original product folder. This is the second reason for the difference, as this value can thus not be used for the determining the dry particle density.

Water absorption according to pyknometer test
The 24h water absorption of lava stone found with the pyknometer test is 6.6%, which is in accordance with the value used for determining the mix designs of the first series of pervious concrete (Table B.1. The water absorption of pumice stone determined by testing is 63% with a standard deviation of 0.53%, which is lower than the estimated value. The water absorption of 63% determined with the pyknometer test is assumed correct, since the low standard deviation indicates that this test is reliable. Furthermore, the quick test for estimating the water absorption is performed on a different fraction which makes the estimated value less valid. The use of a different fraction can explain the difference in result, as the contact area of a smaller fraction is higher, resulting in a higher 24h water absorption.

Table B.1

	Lava stone		Pumice stone	
	Estimated	Tested	Estimated	Tested
Dry particle density [kg/m^3]	2580	2574.2	1287	870.4
24h Water absorption [%]	6.5	6.6	68	63

B.3. Error due to false assumptions

The estimated dry particle densities of pumice stone and lava stone are used to determine the mix designs for the first series of pervious concrete. The estimated dry particle density of lava stone is in accordance with the result obtained with the pyknometer test, but the assumed dry particle density for pumice stone is incorrect. Therefore, the ACRs of mix designs C1.3 and C1.4 are higher compared to the ACRs of mix design C1.1 and C1.2. The difference between the estimated water absorption of pumice aggregate and the water absorption determined with the pyknometer test, also effects the ACRs and thus contributes to the fact that fair comparison between the mix designs with pumice stone (C1.1 and C1.2) and with lava stone (C1.3 and C1.4) is impossible. Unknowingly one more parameter is namely varied. The trends that are seen for the aggregate type parameter are also the result of the different ACR. The difference that is caused by the error is determined below.

The recipes used for casting the samples of the first series of pervious concrete are included in Table B.2. With the correct dry densities and water absorption determined with the pyknometer test these recipes are transformed to volumes, resulting in the ACRs from Table B.3. These values show that the ACR of mix design C1.1 and C1.2 is approximately 1.5 times bigger than the ACR of mix design C1.3 and C1.4. This means that C1.1 and C1.2 contain only 66% of the cement paste volume of C1.3 and C1.4, resulting in a thinner cement paste layer coating the pumice stone aggregates. For completeness the correct recipes that should have been casted for the first series of pervious concrete based on the pyknometer results are included in Table B.4.

Table B.2: Mix designs that are casted to make the samples for the first series of pervious concrete

	C1.1	C1.2	C1.3	C1.4
Wet aggregate [g]	Confidential	Confidential	Confidential	Confidential
Water [g]	Confidential	Confidential	Confidential	Confidential
Cement [g]	Confidential	Confidential	Confidential	Confidential

Table B.3: Mix designs that are casted to make the samples for the first series of pervious concrete converted to volumes with the correct dry particle density and water absorption of pumice stone

Series	C1.1	C1.2	C1.3	C1.4
Aggregate [L]	Confidential	Confidential	Confidential	Confidential
Water [L]	Confidential	Confidential	Confidential	Confidential
Cement [L]	Confidential	Confidential	Confidential	Confidential
ACR [-]	6.006	6.006	4.062	4.062

Table B.4: Correct mix designs for the first series of pervious concrete with a constant ACR

Series	C1.1	C1.2	C1.3	C1.4
Wet aggregate [g]	Confidential	Confidential	Confidential	Confidential
Water [g]	Confidential	Confidential	Confidential	Confidential
Cement [g]	Confidential	Confidential	Confidential	Confidential

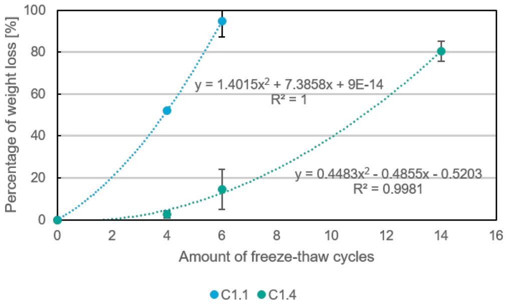
C
Appendix: Prediction freeze-thaw resistance

A mix design similar to C2.1 with pumice stone aggregate instead of lava stone aggregate is interesting for improving the water absorption capacity of the pervious concrete. This mix design is not tested in the experimental phase, so it is unknown if this mix design fulfils the technical requirements. As especially the freeze-thaw resistance of the mix designs with pumice stone of the first series is under performing, the freeze-thaw resistance is important to determine the potential of this mix design.

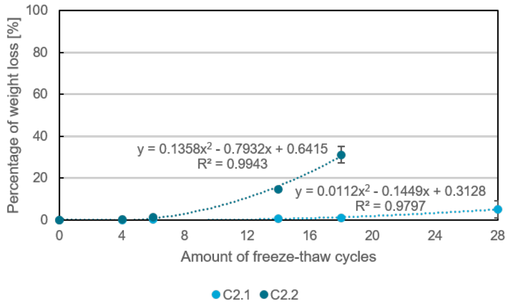
To predict the number of FT cycles after which the mass loss is higher than the limit of 25%, the results of the first and the second series are compared. In the first series of pervious concrete pumice stone aggregate is tested, but only in combination with a WCR of 0.6 and 0.8 and an ACR of 6. As the freeze-thaw resistance for a mix design with a WCR of 0.4 and an ACR of 2 should be estimated, the effect of those parameters should be determined based on the series tested with lava stone.

The results of C1.4 and C2.2 are compared to determine the effect of the decrease of the ACR. Those mix designs are both made with lava stone aggregate and are made with a WCR of 0.6. The aggregate fraction differs slightly, but as the results of the first series indicate that the range for which the aggregate fraction is varied is too small, it is assumed that the difference in the aggregate fraction does not influence the freeze-thaw resistance. The ACR of mix design C1.4 is 4 and the ACR of mix design C2.2 is 2. The results of C2.1 and C2.2 are compared to determine the effect of the decrease of the WCR. Both mix designs are made with lava stone aggregate and an ACR of 2. Mix design C2.1 is made with a WCR of 0.4 and mix design C2.2 is made with a WCR of 0.6. The difference in results can thus be attributed to the difference in WCR.

The number of FT cycles after which the mass loss limit of 25% is exceeded, is determined with polynomial second order trendlines as shown in Figure C.1. The results are included in Table C.1. The number of cycles until the mass loss limit is reached is increased by a factor of 2.13 when the ACR is decreased from 4 to 2 for the samples made with lava stone aggregate and a WCR of 0.6. As the only freeze-thaw results including pumice stone are from the mix design with an ACR of 6, the factor of increase is even higher. It is assumed that the number of FT cycles is increased by $2.13^{1.5} = 3.11$ when the ACR is reduced from 6 to 2. If the WCR is decreased from 0.6 to 0.4 for the samples made with lava stone aggregate, the FT cycles until a mass loss of 25% is increased by a factor of 3.1. Together this means that the number of FT cycles for C1.1 is multiplied by the factor of 9.7. This results in a prediction of the FT limit of 19.3 cycles.



(a) for the first series



(b) for the second series

Figure C.1: Polynomial second order trendlines for mass loss during FT cycles

Table C.1: Overview of the properties of the relevant mix designs and the number of FT cycles after which the mass loss limit of 25% was reached during testing based on the polynomial trendlines

	Aggregate Type	WCR	ACR	FT cycles *
C1.1	Pumice stone	0.6	6	2
C1.4	Lava stone	0.6	4	8
C2.1	Lava stone	0.4	2	53
C2.2	Lava stone	0.6	2	17

* after which mass loss >25%

D

Appendix: Multi-criteria analysis

In this Appendix a more elaborated explanation on the multi-criteria analysis (MCA) which is performed in paragraph 9.4 is given.

D.1. Background & Procedure

Multi-criteria analysis are frequently used since the late 20th century and consider multiple objectives and criteria in decision-making problems. This means a MCA is used for multi-dimensional problems, which usually involve conflicting values. A MCA does not constitute of one specific method, but can be performed by a number of techniques. Typically, the performance of an option is scored on various criteria which can be assigned different weights to eventually rank the options.
A multi-criteria analysis consists of some key-elements, that should be established in the following seven steps (Dean, 2022). However, the order of the steps is not fixed, but can vary based on the problem that is considered as is visualised in Figure D.1. For now the steps are considered in the following order:

1. Primary problem analysis

   Beforehand, a thorough problem analysis should be done to understand the nature of the problem and to define the scope. Based on this an appropriate MCA technique and an appropriate order of steps can be chosen for the MCA analysis. This step basically sets the boundaries for the framework of the analysis.

2. Identification of objectives and associated criteria

   From the fundamental values, the general goals can be identified. These goals form the base of the objectives. The number of objectives is not predefined but is dependent on the problem. Thorough and in-depth assessment require a comprehensive list of objectives, which should contain more than a few key aspects, but the total number of objectives should be manageable. Criteria are used to measure the extent to which the objectives are met as precisely and clearly as possible. The criteria should be exhaustive, meaning that all important aspects should be considered, but should not be excessively similarly to other criteria to avoid double counting.

3. Weighting the criteria

   The weighting of the criteria is sensitive to errors, since there is value judgement which has a strong influence on the end result. Minor changes to the weights, can cause major changes in the end result.

4. Development of the options to be assessed

   A list of the options included in the analysis should be made. The options are associated to the primary problem that should be solved. The suitable number of options included in the MCA is depended on the primary problem and the extensiveness of the analysis.

5. Construction of the performance profile of each option

   When step 1 to 4 are performed the performance profile for all the alternatives is made. Both quantitative and qualitative data can be included in this performance profile.

6. Scoring of impacts of each option

   The data from the performance profiles should be converted to a common scale by means of performance scores. Performance scores represent numbers with no unit attached. Converting the information from the performance profile to performance scores includes some subjectivity that is hard to avoid. Several scales can be chosen for the performance scores, for example a Likert-type scale. When using a Likert-type scale, the distance between the values is unclear. The width of the scale should carefully be chosen, to be able to clearly identify the differences in performance between two alternatives. However, when the knowledge of the performance of the alternatives is limited a narrow scale is most suitable.

7. Combining of scores and weights to rank the options

   To rank the alternatives, all the above steps should be combined to the final result.

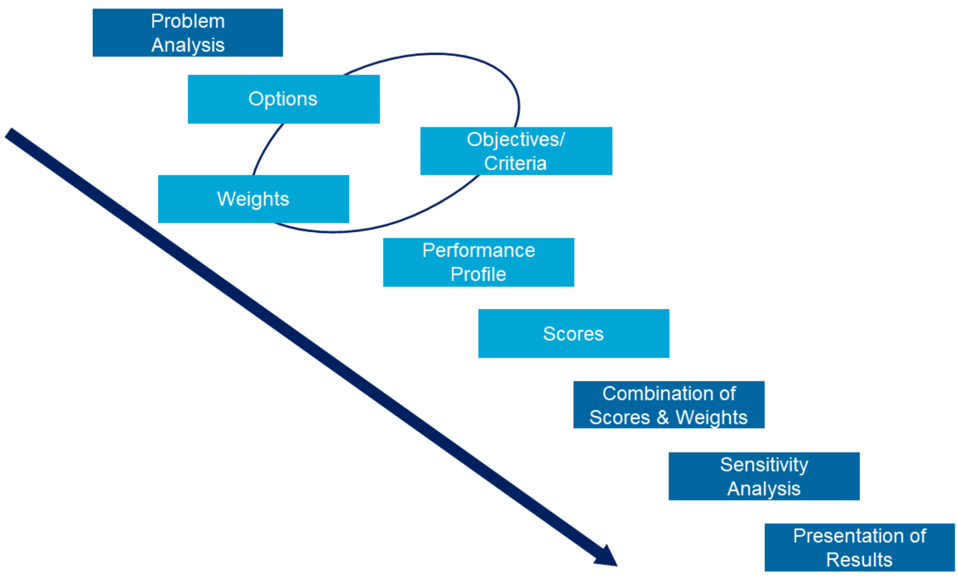


Figure D.1: Order of steps in the MCA (Dean, 2022)

D.2. Weighting the criteria

The weight of each objective is determined in paragraph 9.4.3. The distribution of the weight over the criteria is based on own judgement. This results in the weights per criteria that are given in Table D.1.

Table D.1: Score and weight per criteria

Criteria	Score	Weight
[1a] Water retention volume	2	0.133
[1b] Water loss speed	0.5	0.033
[1c] Water replenishment speed	0.5	0.033
[1d] Dependency on rainfall or manual replenishment	2	0.133
Total of water storage criteria	**5**	
[2a] Type and amount of targeted species and other vegetation	2.5	0.167
[2b] Type and amount of other organisms	1	0.067
Total of biodiversity value criteria	**3.5**	
[3a] Physical boundaries	1	0.067
[3b] Technology readiness level	0.5	0.033
[3c] Production complexity	1.5	0.100
[3d] End-of-life options	0.5	0.033
Total of technical feasibility criteria	**3.5**	
[4a] Production costs	0.5	0.033
[4b] Material costs	0.5	0.033
[4c] Environmental costs	1	0.067
Total of economic feasibility criteria	**2**	
[5a] Predicted life time	1	0.067
Total of durability criteria	**1**	

D.3. Factors associated to the criteria

For scoring the performance of the options per criteria, the factors from Table D.2 are considered.

D.4. Performance profiles of the options

The performance profile of option 1, which is the option with a water reservoir in the capping stone, is included in Table D.3. The performance profile of the second option, which is the option with a capillary material in the cavity, is included in Table D.4. The performance profile of the third option, which is the option with a capillary material in vertical tubes in the pervious layer is included in Table D.5.

Table D.2: Factors influencing the scoring of the options per criteria

Criteria	Factors
[1a] Water retention volume	- Space available for water storage in material - Restricted by the amount of material that can be incorporated in the solution
[1b] Water loss speed	- Surface area - Coverage with another layer - Thickness/Amount of retentive material - Capillarity of retentive material
[1c] Water replenishment speed	- Surface area - Thickness/Amount of retentive material - Capillarity of retentive material
[1d] Dependency on rainfall or manual replenishment	- Ability to use canal water as a water source or ability of buffering rainwater for later use
[2a] Type and amount of targeted species and other vegetation	- Impact on the other properties that impact vegetation (acidity, nutrient availability, surface roughness and root ability) - Area suitable for vegetation
[2b] Type and amount of other organisms	- High surface roughness and niches have a positive effect on organisms
[3a] Physical boundaries	- Thickness of the design - Weight of the design
[3b] Technology readiness level	- Amount of knowledge on the working principle - Amount of knowledge in this type of application
[3c] Production complexity	- Amount of production steps - Difficulty of production steps
[3d] End-of-life options	- Potential for up cycling/recycling/down cycling - Potential for separation of materials at end-of-life
[4a] Production costs	- Labor intensity of production process - Necessity of expensive equipment
[4b] Material costs	- Amount of extra materials compared to standard design - Costs of materials
[4c] Environmental costs	- MKI-value of materials
[5a] Predicted life time	- The need for intermediate replacement - The need for maintenance

Table D.3: Performance profile of system modification with a water reservoir in the capping stone (option 1)

Criteria	Performance
[1a] Water retention volume	Volume of reservoir is adjustable to needs, by adjusting the dimensions of the capping stone and will thus not be a restriction. Volume of water directly available to the vegetation is restricted to the water retention capacity of the pervious concrete and the soil in the macro-pores.
[1b] Water loss speed	Water loss from reservoir is partly determined by the k-value of the water permeable distributing material. Additionally, water evaporates directly from reservoir, which is mostly depended on the k-value of the water permeable pavement, the outside temperature and the relative humidity as other factors such as wind play a less important role inside the reservoir. Open water evaporation is faster than evaporation from a water retaining material.
[1c] Water replenishment speed	The reservoir can be filled in a short period during rain showers, as water from city surfaces flows to the canals and is intercepted in the reservoir. The inflow in restricted by the k-value of the water permeable pavement, so an appropriate k-value should be chosen to obtain fast inflow of water. The surface area of the reservoir is relatively small compared to the volume of water that is stored in the reservoir.
[1d] Dependency on rainfall or manual replenishment	The reservoir decreases the dependency on rainfall and manual replenishment. Due to outflow and evaporation it is possible that the reservoir is emptied during long periods of drought. So the design is not completely independent of rainfall and manual replenishment. However, the reservoir can manually be filled if needed.
[2a] Type and amount of targeted species and other vegetation	Accumulation of nutrients can occur in reservoir, which might help establishment of plants, but can also cause overgrowing of less valued species. Vegetation can occur on the capping stone which is beneficial for the amount of vegetation on the quay wall.
[2b] Type and amount of other organisms	Unknown
[3a] Physical boundaries	The height of the horizontal part is increased with approximately 40 cm. No extra weight on the structural layer.
[3b] Technology readiness level	Rainwater harvesting with water permeable concrete is the subject of many papers and is encountered in similar applications, but is not yet tested in this exact application
[3c] Production complexity	Simple production process, but some more steps than design without system modifications
[3d] End-of-life options	Separation of the two layers is difficult. Down cycling of the product is possible.
[4a] Production costs	The production process is not labor intensive and no additional equipment is needed, except from different casting molds appropriate for creating an element with reservoir.
[4b] Material costs	Not a lot of extra materials are needed, as the reservoir is mostly empty volume. Extra materials for this system modification can be cheap materials such as water permeable concrete and watertight concrete.
[4c] Environmental costs	The MKI-value of concrete is high, but the MKI-value of pervious concrete is lower as less cement is used in the mix design, which is the most hazardous component in pervious concrete.
[5a] Predicted life time	Intermediate maintenance is needed to prevent clogging of the water permeable pavement in the top layer of the capping stone.

Table D.4: Performance profile of system modification with capillary substrate in the cavity (option 2)

Criteria	Performance
[1a] Water retention volume	With a cavity thickness of 100 mm filled with BVB substrate with a water holding capacity of 40 vol-%. This results in sufficient water volume according to the reference project in Delft.
[1b] Water loss speed	Water loss is determined by evaporation. Due to coverage of the capillary layer with the finishing layer, direct evaporation from the capillary layer is not occurring. When water evaporates from the finishing layer, this layer extracts water from the capillary substrate layer, so in this way water is lost.
[1c] Water replenishment speed	The water replenishment speed is depended on the capillary rise rate. It is sufficient most of the time, except when evaporation is too fast. In that case the water transport in the capillary layer is not sufficient for compensating the losses as is seen in the reference project in Delft.
[1d] Dependency on rainfall or manual replenishment	The capillary substrate layer is independent on rainfall and manual replenishment. Water transport in the capillary layer is not sufficient when evaporation rates are high for keeping the plants alive. However, revival of most plants is possible since the roots did not die.
[2a] Type and amount of targeted species and other vegetation	The capillary substrate layer is not influencing the other properties associated to the establishment of vegetation.
[2b] Type and amount of other organisms	The capillary substrate layer is not influencing the establishment of other organisms.
[3a] Physical boundaries	The thickness of the vertical part is increased by 100 cm, which also results in extra weight on the structural layer.
[3b] Technology readiness level	The use of a capillary substrate layer in the cavity of a quay wall is tested in many projects. It is not yet tested in combination with pervious concrete.
[3c] Production complexity	Complicated as the pervious layer has to be connected to the structural layer after hardening of the layers, resulting in much more steps than the design without system modifications.
[3d] End-of-life options	Two layers can easily be separated and can be used recycled or down cycled.
[4a] Production costs	Labor intensive production process.
[4b] Material costs	Substrate added to the cavity is not expensive, but anchor bolts for the connection of the two layers are expensive.
[4c] Environmental costs	The MKI-value of steel is approximately half of that of concrete and the MKI value of substrate is low, so the extra materials used for this system modification are low.
[5a] Predicted life time	No intermediate maintenance is needed for the capillary layer.

Table D.5: Performance profile of system modification with capillary substrate in vertical tubes (option 3)

Criteria	Performance
[1a] Water retention volume	The thickness of the pervious layer is increased to be able to make tubes excavations which can be filled with a capillary material. A thicker pervious layer also contributes to the water retention of the quay wall as the pervious concrete and the substrate in the macro-pores also retain water. Therefore an increase in thickness equal to option 2 is assumed to be sufficient even though the volume of the capillary material is in that case lower than for option 2.
[1b] Water loss speed	Water loss is determined by evaporation. Due to coverage of the capillary layer with the finishing layer, direct evaporation from the capillary layer is not occurring. When water evaporates from the finishing layer, this layer extracts water from the capillary substrate layer, so in this way water is lost.
[1c] Water replenishment speed	The water replenishment speed is depended on the capillary rise rate. As less capillary material is included than in option 2, capillary rise volume is not sufficient at all times (scenario with the 50 mm substrate layer in the quay wall project in Delft).
[1d] Dependency on rainfall or manual replenishment	The capillary substrate layer is independent on rainfall and manual replenishment. Water transport in the capillary layer is not sufficient when evaporation rates are high for keeping the plants alive and revival of most plants is not possible or is taking a lot of time.
[2a] Type and amount of targeted species and other vegetation	The thickness of the pervious layer is increased which might be beneficial for the root ability of the pervious layer.
[2b] Type and amount of other organisms	The capillary substrate layer is not influencing the establishment of other organisms.
[3a] Physical boundaries	The thickness of the vertical part is increased by 100 cm, which also results in extra weight on the structural layer. The weight might be a bit higher than for option 2, but the difference is low as most of the weight is from the absorbed water.
[3b] Technology readiness level	The use of capillary substrate in tubes in pervious layer is not encountered in literature.
[3c] Production complexity	Complicated production process as excavations in the pervious concrete are needed. Not a lot of extra steps as the two layers can be casted onto each other.
[3d] End-of-life options	Separation of the two layers is difficult. Down cycling of the product is possible.
[4a] Production costs	Making appropriate moulds is labor intensive, but when a proper mould is available the production process is only limited by assuring that the pervious concrete is completely filling the mould.
[4b] Material costs	Extra materials needed for this system modification are pervious concrete and capillary substrate. This are cheap materials.
[4c] Environmental costs	The MKI-value of concrete is high, but the MKI-value of pervious concrete is lower as less cement is used in the mix design, which is the most hazardous component in pervious concrete.
[5a] Predicted life time	No intermediate maintenance is needed for the capillary tubes.

E

Appendix: Monitoring images of the Quay Wall Garden Project in Delft

(a) June the 7th

(b) July the 8th

(c) August the 1st

Figure E.1: Pictures of the set-up of the experiment of the Quay Wall Garden Delft project at different moments

(d) August the 12th

(e) August the 23th

(f) September the 6th

(g) September the 20th

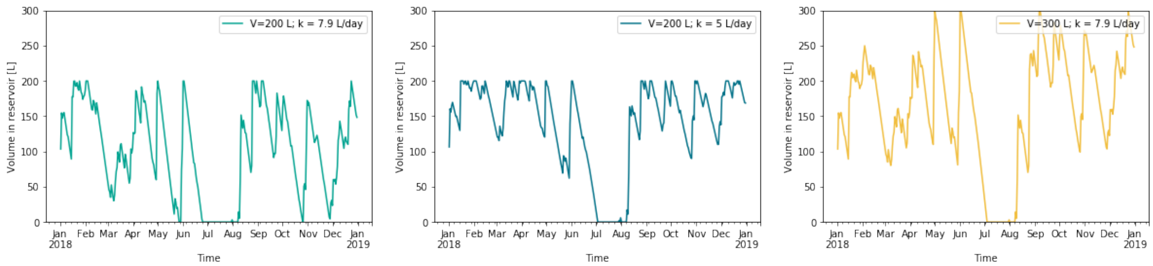
Figure E.1: Pictures of the set-up of the experiment of the Quay Wall Garden Delft project at different moments

F Appendix: Model of the reservoir and the substrate layer

F.1. Reservoir

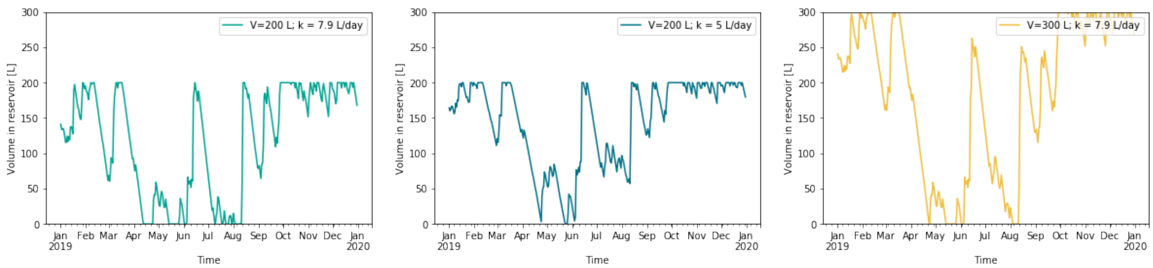
In this part of the Appendix the results for modelling the reservoir with different reservoir volumes and different k-values for the water permeable outlet are included.

Reservoir type a	:	Reservoir with V = 200 L/m and k = 7.9 L/day/m
Reservoir type b	:	Reservoir with V = 200 L/m and k = 5.0 L/day/m
Reservoir type c	:	Reservoir with V = 300 L/m and k = 7.9 L/day/m



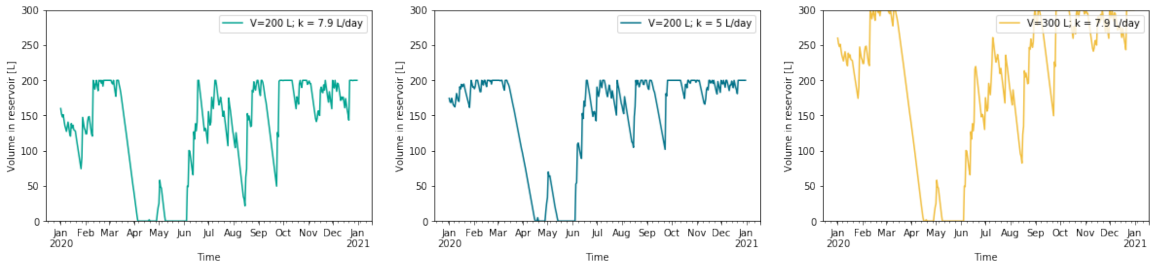
(a) Reservoir with a volume of 200 L/m and a k-value of 7.9 L/day/m (b) Reservoir with a volume of 200 L/m and a k-value of 5.0 L/day/m (c) Reservoir with a volume of 300 L/m and a k-value of 5.0 L/day/m

Figure F.1: Modelled water volume in the reservoir in the year 2018 based on the data from the KNMI of the weather station in Rotterdam



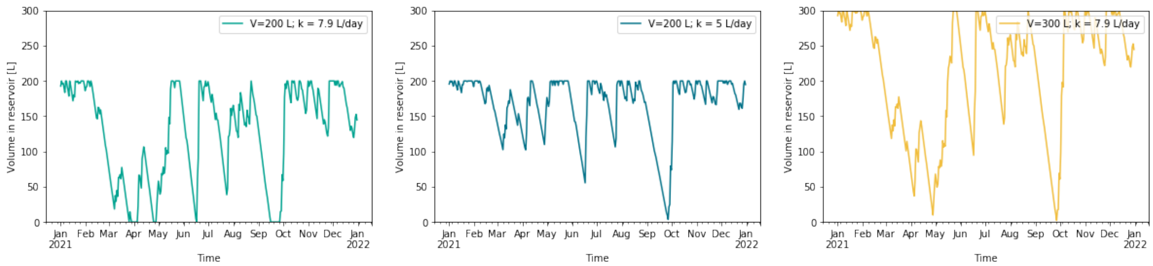
(a) Reservoir with a volume of 200 L/m and a k-value of 7.9 L/day/m (b) Reservoir with a volume of 200 L/m and a k-value of 5.0 L/day/m (c) Reservoir with a volume of 300 L/m and a k-value of 5.0 L/day/m

Figure F.2: Modelled water volume in the reservoir in the year 2019 based on the data from the KNMI of the weather station in Rotterdam



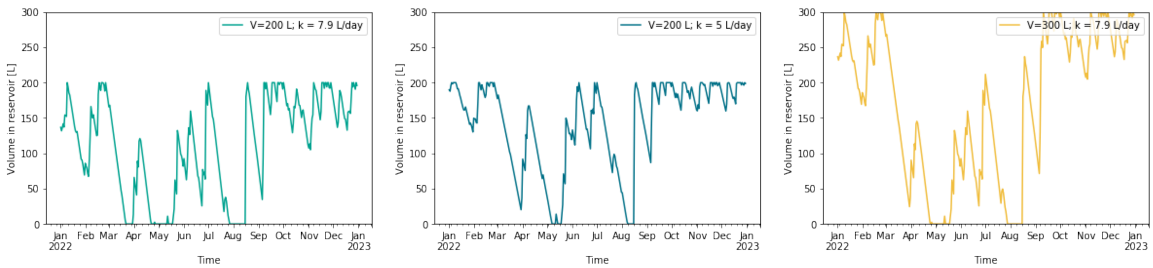
(a) Reservoir with a volume of 200 L/m and a k-value of 7.9 L/day/m (b) Reservoir with a volume of 200 L/m and a k-value of 5.0 L/day/m (c) Reservoir with a volume of 300 L/m and a k-value of 5.0 L/day/m

Figure F.3: Modelled water volume in the reservoir in the year 2020 based on the data from the KNMI of the weather station in Rotterdam



(a) Reservoir with a volume of 200 L/m and a k-value of 7.9 L/day/m (b) Reservoir with a volume of 200 L/m and a k-value of 5.0 L/day/m (c) Reservoir with a volume of 300 L/m and a k-value of 5.0 L/day/m

Figure F.4: Modelled water volume in the reservoir in the year 2021 based on the data from the KNMI of the weather station in Rotterdam



(a) Reservoir with a volume of 200 L/m and a k-value of 7.9 L/day/m (b) Reservoir with a volume of 200 L/m and a k-value of 5.0 L/day/m (c) Reservoir with a volume of 300 L/m and a k-value of 5.0 L/day/m

Figure F.5: Modelled water volume in the reservoir in the year 2022 based on the data from the KNMI of the weather station in Rotterdam

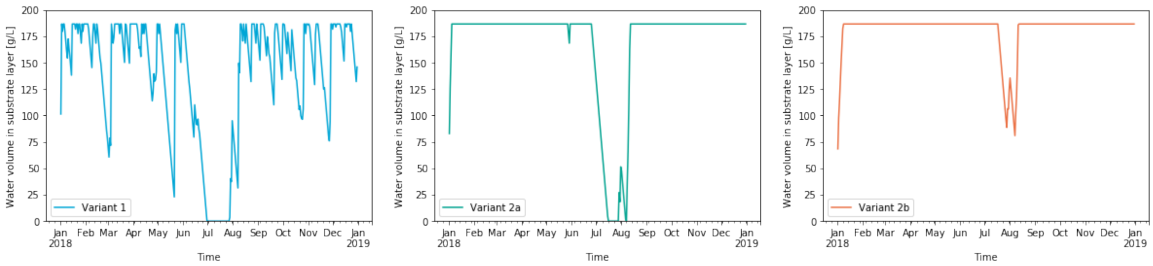
F.2. Substrate layer

In this part of the Appendix the results for modelling the moisture content in the substrate layer for the different variants are included.

Variant 1 : Design without reservoir
Variant 2a : Design with reservoir with V = 200 L / m and k = 7.9 L / day / m
Variant 2b : Design with reservoir with V = 300 L / m and k = 5.0 L / day / m

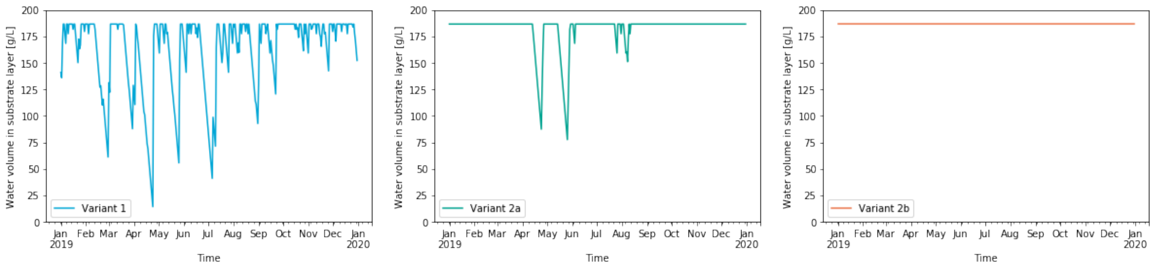
F.2.1. Scenario 1

The inflow-outflow model of scenario 1 is based on the climate chamber conditions (T = 20 ± 2 °C & RH = 55 ± 5 %) to determine the evaporation rate.



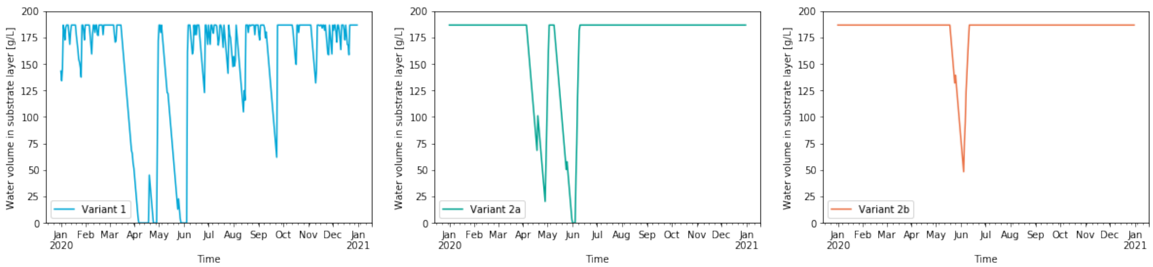
(a) Design variant 1 (b) Design variant 2a (c) Design variant 2b

Figure F.6: Modelled water volume in the substrate layer in the year 2018 for scenario 1 (T = 20 ± 2 °C & RH = 55 ± 5 %)



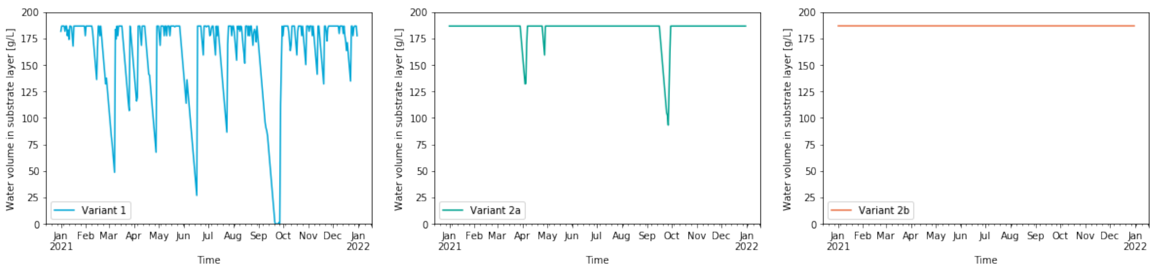
(a) Design variant 1 (b) Design variant 2a (c) Design variant 2b

Figure F.7: Modelled water volume in the substrate layer in the year 2019 for scenario 1 (T = 20 ± 2 °C & RH = 55 ± 5 %)



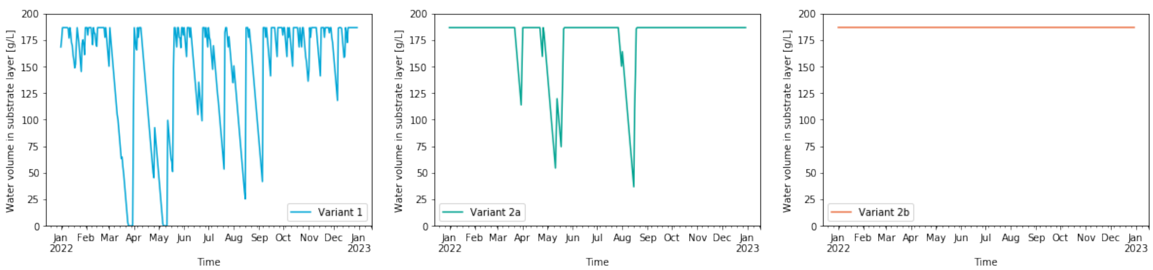
(a) Design variant 1 (b) Design variant 2a (c) Design variant 2b

Figure F.8: Modelled water volume in the substrate layer in the year 2020 for scenario 1 (T = 20 ± 2 °C & RH = 55 ± 5 %)



(a) Design variant 1 (b) Design variant 2a (c) Design variant 2b

Figure F.9: Modelled water volume in the substrate layer in the year 2021 for scenario 1 (T = 20 ± 2 °C & RH = 55 ± 5 %)

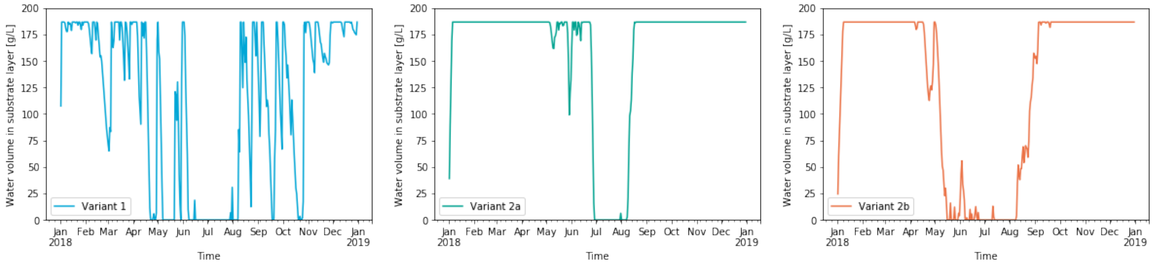


(a) Design variant 1 (b) Design variant 2a (c) Design variant 2b

Figure F.10: Modelled water volume in the substrate layer in the year 2022 for scenario 1 (T = 20 ± 2 °C & RH = 55 ± 5 %)

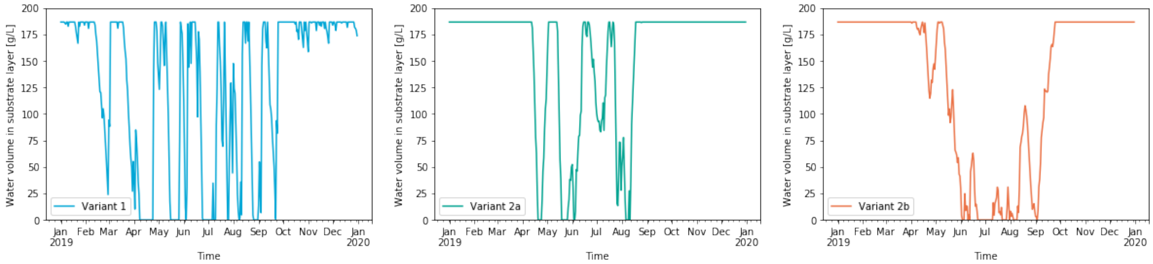
F.2.2. Scenario 2

The inflow-outflow model of scenario 2 is based on the reference crop evapotranspiration data calculated by the KNMI to determine the evapotranspiration rate of the substrate layer.



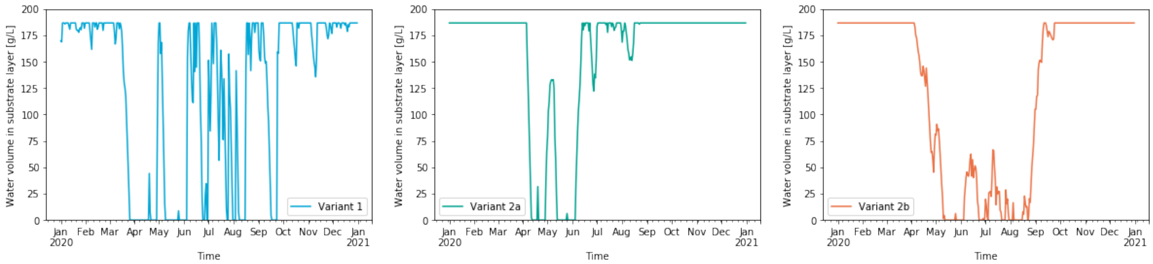
(a) Design variant 1 (b) Design variant 2a (c) Design variant 2b

Figure F.11: Modelled water volume in the substrate layer in the year 2018 for scenario 2 (T = 20 ± 2 °C & RH = 55 ± 5 %)



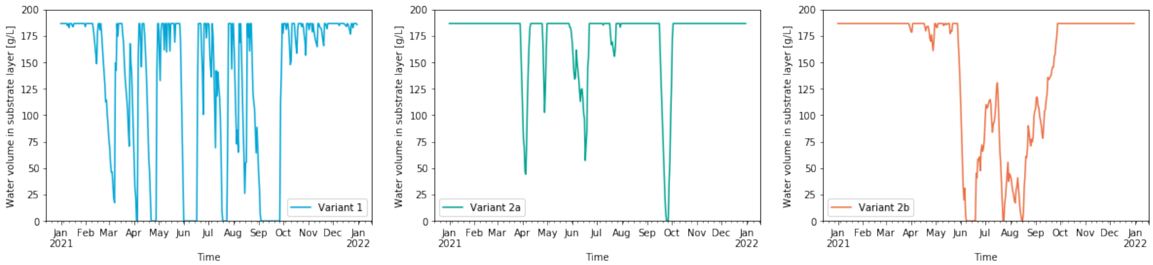
(a) Design variant 1 (b) Design variant 2a (c) Design variant 2b

Figure F.12: Modelled water volume in the substrate layer in the year 2019 for scenario 2 (T = 20 ± 2 °C & RH = 55 ± 5 %)



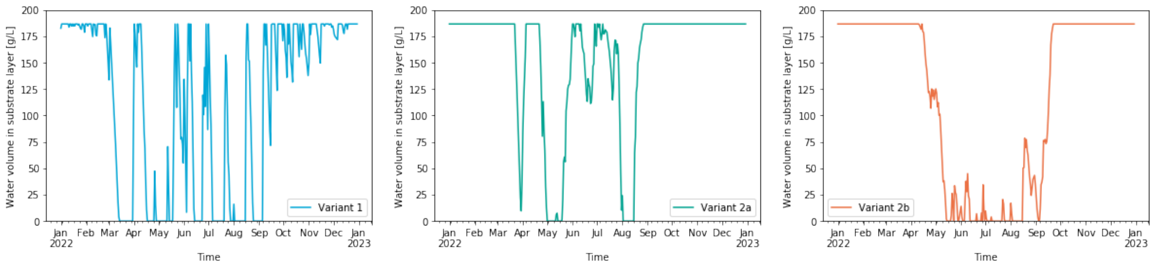
(a) Design variant 1 (b) Design variant 2a (c) Design variant 2b

Figure F.13: Modelled water volume in the substrate layer in the year 2020 for scenario 2 (T = 20 ± 2 °C & RH = 55 ± 5 %)



(a) Design variant 1 (b) Design variant 2a (c) Design variant 2b

Figure F.14: Modelled water volume in the substrate layer in the year 2021 for scenario 2 (T = 20 ± 2 °C & RH = 55 ± 5 %)



(a) Design variant 1 (b) Design variant 2a (c) Design variant 2b

Figure F.15: Modelled water volume in the substrate layer in the year 2022 for scenario 2 (T = 20 ± 2 °C & RH = 55 ± 5 %)

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