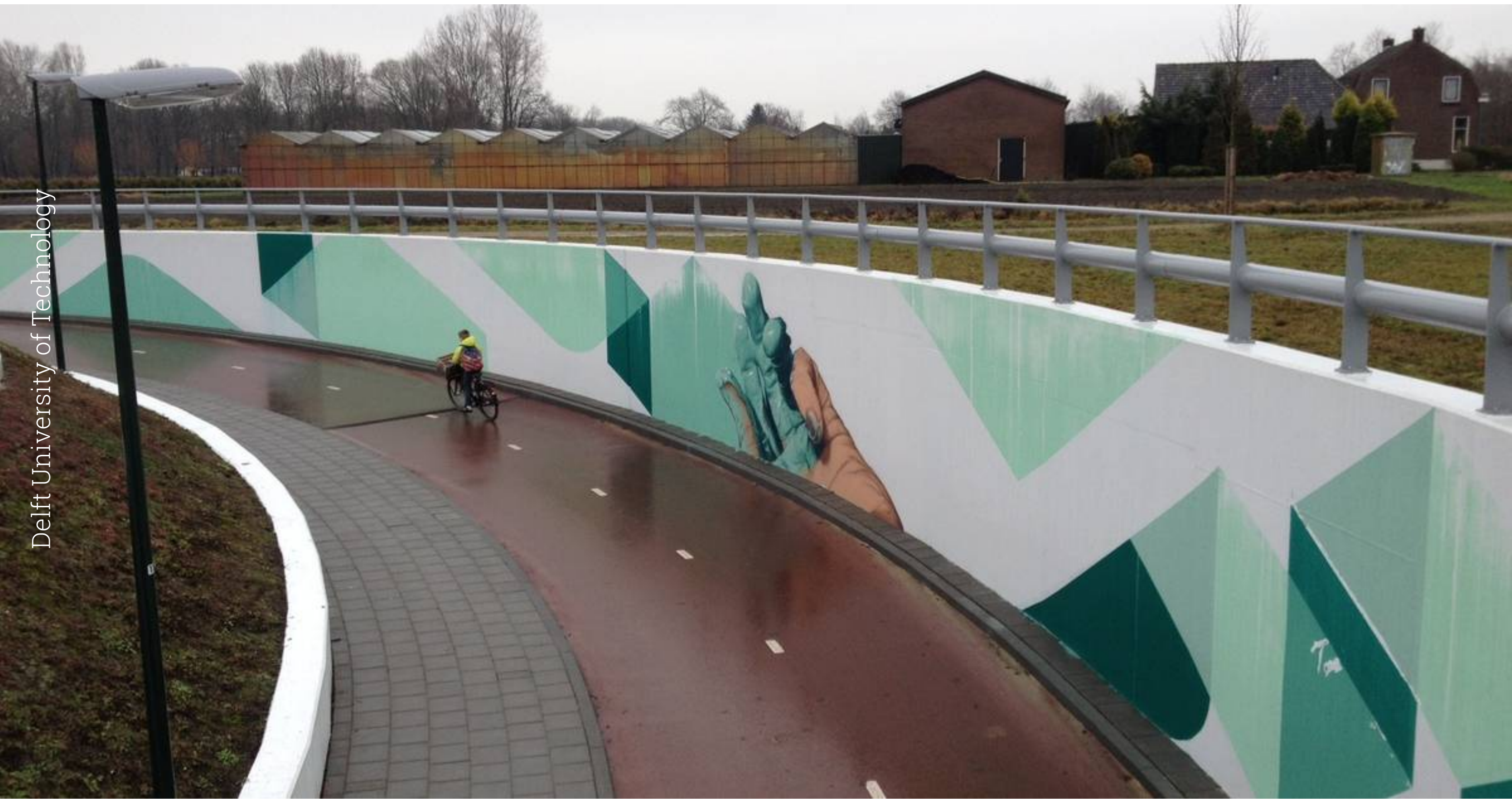
Developing sustainable and bioreceptive concrete mix design for vertical greening systems in the Netherlands

Vaia Kladou



Developing sustainable and bioreceptive concrete mix design for vertical greening systems in the Netherlands

by

Vaia Kladou

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Preface

This thesis presents my research on developing a sustainable and bioreceptive concrete mix design for vertical systems in the building envelope. It is written in the frame of finishing my master of Environmental Engineering with a specialization in Resource and Waste Engineering at TU Delft, Netherlands.

During this thesis, there are several people I would like to thank and express my gratitude to. First of all, a big thank you to Dr. ir. M. Ottelé and Max Veeger for their great support, discussions, and critique. Their constructive comments and feedback helped me progress in the research, and their approachability was of great importance to me. I also want to thank Tom van Rijswijk from Holcim for guiding me through the process, providing support, and for provision of resources. Additionally, from the committee, I would like to thank Eric-Jan Houwing for his feedback and critique.

Beyond the committee, there are others I wish to acknowledge: the technical staff from TU Delft and the industry. Maiko van Leeuwen (TU Delft), Ton Blom (TU Delft), and John van den Berg (TU Delft), all of whom helped me with the experimental equipment and explained its operation. A special thank you to Baptiste Vivier, Vincent Morin, Isabelle Dubois-Brugger, Florian Maurice, and Anthony Peuchlestrade from the Holcim Innovation Center for their feedback and advice on the research proposal.

Of course, the support from people not directly involved in the research has been invaluable to me. Thank you mom and dad for supporting me with advice and motivational words during these two years of my master's studies. A big thank you to my sister and brother, who listened to all my concerns during this research and supported me through long phone discussions. Lastly, I would like to thank my friends who encouraged me, whether from the Netherlands or Greece.

Vaia Kladou
Delft, August 2024

Summary

Urbanization has led to environmental challenges such as the Urban Heat Island effect and the reduction of green spaces, resulting in lower carbon dioxide absorption, increased air pollution, and higher noise levels. Incorporating vegetation into buildings through vertical or horizontal greening systems can address these issues. However, these systems face challenges like high irrigation costs, artificial substrates, low integration, and short lifespans compared to building infrastructure. Bioreceptive materials offer a promising alternative by allowing greenery to grow directly on the material, bypassing these limitations. This research focuses on enhancing the bioreceptivity of concrete while evaluating its sustainability performance and structural integrity in terms of compressive strength (CS), and freeze-thaw resistance (FT).

The type of concrete being evaluated is porous concrete, designed to include a growing substrate for hosting plants. A multi-criteria analysis is used to determine the optimal concrete mix, considering three design criteria: bioreceptivity, sustainability, and structural integrity (including compressive strength and freeze-thaw resistance). Three mix designs are developed: a reference mix with Ordinary Portland Cement (OPC) and limestone aggregates, and two mixes using a low-carbon Calcined Clay (C^3) binder—one with lava stone (Mix 1) and the other with recycled concrete aggregates (Mix 2). An iterative process is employed to adjust the binder and water content, evaluating workability, compressive strength after 5 days, and interconnected porosity. Once suitable proportions are achieved, the concrete samples are tested for their mechanical, bioreceptive, and sustainable properties. The incorporation of the substrate has also been tested, addressing a gap in the existing literature.

The compressive strength after 28 days was comparatively low for all tested mix designs due to high porosity, with achieved values as follows: Mix 1 (2.5 MPa), Mix 2 (3 MPa), and the reference mix (10 MPa). A decrease in compressive strength was observed when incorporating the growing substrate and after drying. Despite low compressive strength, all samples demonstrated resilience in freeze-thaw resistance, withstanding 28 FT cycles with low mass loss. However, Mix 1 and Mix 2 showed loosening of aggregates when pressed by hand after the standard testing process, indicating a need for further testing of CS after different FT cycles.

Various methods of substrate incorporation were evaluated, showing that the substrate did not penetrate the concrete pores but remained on the surface of the cubes. This did not negatively affect the bioreceptivity for plant growth. The volume of substrate incorporated per sample and mix design varied due to manual application and the surface connectivity of the aggregates for each concrete product. This variability in substrate volume affected the water absorption and retention results, suggesting that these outcomes do not consistently characterize the mix design but rather are variable. However, Mix 1 and Mix 2 exhibited high water absorption rates when considering the concrete product itself (Mix 1 = 164.4 g/L, Mix 2 = 134.1 g/L, Ref mix = 82.4 g/L). Lastly, leaching of elements from the concrete layer occurred, leading to an increase in the pH of the incorporated growing substrate. All samples showed germination after one month of testing, with Mix 1 displaying the highest average germination rate and dry biomass. However, Mix 2 and the reference mix exhibited high variance in plant growth results, likely due to varying outdoor conditions such as moisture and temperature. Further testing is recommended to better isolate the impact of these outdoor conditions, which could have contributed to the high variance in plant growth outcomes.

Finally, in terms of sustainability performance, Mix 1 and Mix 2 positively impact the environmental burden of the concrete product by reducing the ECI and CO_2 emissions by an average of 50% per $1m^3$ of concrete, considering LCA stages A1-A3. At the same time, the use of C^3 binder reduces the ECI and CO_2 emissions from the binder material extraction stage by 60% compared to OPC binder, further demonstrating that this binder is a low-carbon alternative.

This research demonstrates that the tested mix designs, evaluated for bioreceptivity, sustainability, and structural integrity (in terms of compressive strength and freeze-thaw resistance), have great potential for use in vertical greening systems with Mix 1 identified as the most optimal concrete mix design. This finding is significant for urban environments, especially as urbanization is expected to increase in the coming years. Bioreceptive vertical greening systems made with sustainable materials can address environmental challenges in cities and align with the Sustainable Development Goals.

Contents

Nomenclature

Abbreviations

Materials	Definition
OPC	Ordinary Portland Cement
GGBFS	Ground Granulated Blast Furnace Slag
MPC	Magnesium Phosphate Cement
FA	Fly Ash
SF	Silica Fume
BFS	Blast Furnace Slag
SB latex	Styrene-butadiene latex
CAC	Calcium Aluminate Cement
CSAC	Calcium Sulfoaluminate Cement
VPC	Vegetation Porous Concrete
SCMs	Supplementary Cementitious materials
MK	Metakaolin
C^3	Calcined Clay Cement
CEC	Crushed Expanded Clay
RCA	Recycled Concrete Aggregate
RBA	Recycled Brick Aggregate
RAP	Reclaimed Asphalt Pavement
SSA	Steel Slag Aggregate
NA	Natural Aggregate

Experimental/Property Terms	Definition
PSD	Particle Size Distribution
W/B	Water to Binder ratio
ABR	Aggregate to Binder ratio
P/M	Phosphate-to-magnesium ratio
FT resistance	Freeze-thaw resistance
ITZ	Interfacial Transition Zone

Other Terms	Definition
UHI	Urban Heat Island
GF	Green Facade
LWS	Living Wall System
SDGs	Sustainable Development Goals
LCA	Life Cycle Assessment
EPD	Environmental Product Declaration
ECI	Environmental Cost Indicator
PEF	Product Environmental Footprint
FU	Functional Unit
C&DW	Construction and Demolition Waste
C2CA	Concrete to Cement and Aggregates

1

Introduction

1.1. Motivation for the research

Urbanization and cities' environmental challenges

During the 20th century, the global urban population grew from 220 million to approximately 2.8 billion, and this number is expected to reach 6.9 billion by 2050, which is about 70% of the world population [1]. Increased urbanization and its related enhanced anthropogenic heat emissions, reduced evaporative cooling, increased surface roughness, lower surface albedos, and narrow urban canyon geometry have resulted in the Urban Heat Island (UHI) effect. [2]. This effect is characterized by higher temperatures in urban areas compared to rural areas, contributing to global warming, heat-related mortalities, and unpredictable climatic changes [3], [4]. Apart from UHI effect, urbanization also results in a decline in green spaces and biodiversity in urban areas, and an increase in building materials used in urban environments [5]. Reduction of greenery in urban areas exacerbates issues like decreased carbon dioxide absorption, elevated noise levels, and increased air pollution, primarily driven by human activities such as traffic and industry [6].

In Figure 1.1 below, the environmental challenges of urbanization are presented, depicting the UHI effect through the difference in late afternoon temperatures between urban and rural areas.

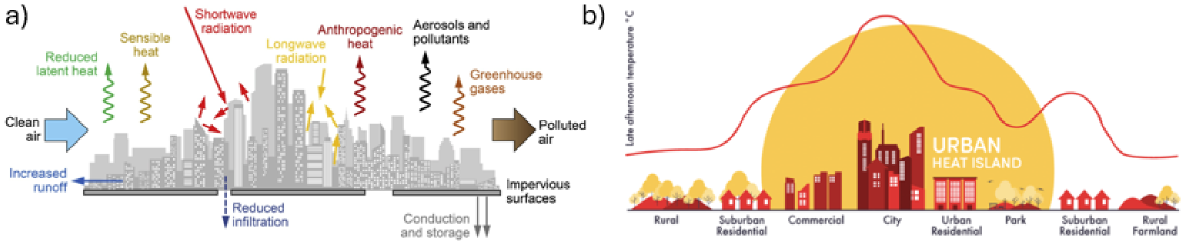


Figure 1.1: Environmental challenges of a) urbanization [7] and b) UHI depiction [8].

To address these issues, there is growing interest in incorporating vegetation into the building envelope using vertical or horizontal greening systems. These systems aim to provide passive climate control and create new ecological habitats to mitigate or fix the environmental issues in urban areas [9]. Horizontal greening systems, are either extensive or intensive green roofs as presented in Figure 1.2 a. They differ from each other by their field of application (flat or sloped roofs), substrate height and weight, vegetation (drought resistance, water, and nutrient requirements), water-retaining capacity, maintenance requirements, and costs [10].

Vertical greening systems can be categorized into two types: green facades (GF) and living wall systems (LWS) as presented in Figure 1.2 b below. GF consist of climbing plants rooted in the subsoil of the buildings and plants can attach either directly to the wall material or in auxiliary frames. LWS are rooted in an artificial substrate or potting soil in planter boxes. Regarding the LWS, an irrigation system should be integrated to meet the water needs of the plants [11], [12].

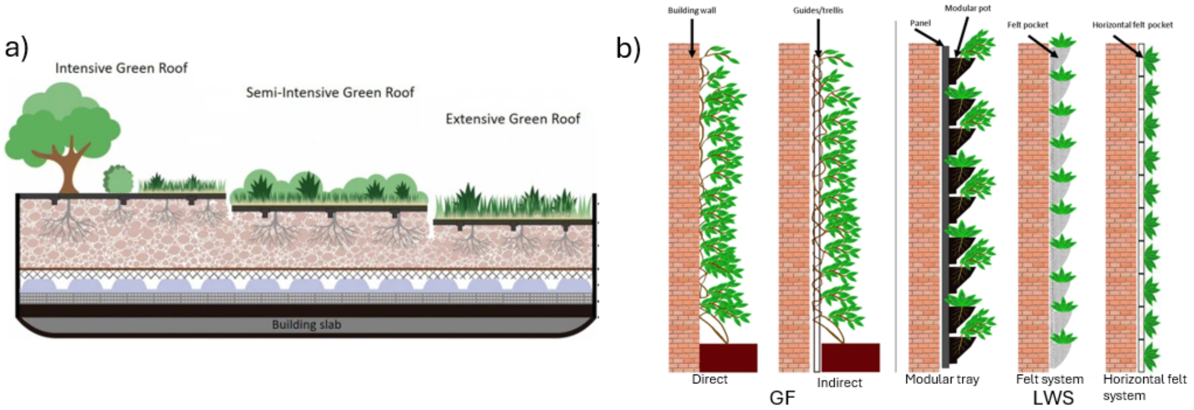


Figure 1.2: Greening systems in the city's envelope: a) Horizontal greening systems [10] and b) Vertical greening systems [13].

Both horizontal and vertical greening systems can increase a building's insulation properties, protecting both its materials and coatings from weather impacts but also decrease the energy demand for heating and cooling for the whole year [14], [15]. Also, they can decrease air pollution levels by trapping pollutants, especially related to the reduction of fine dust levels [16]. They help to control rainwater runoff and increase biodiversity in cities [15]. They can also decrease temperature in the building envelope, providing cooling and shading effect, impacting positively the UHI effect [17]. Besides that, they have the potential to positively impact people's mental health [16], [18].

However, both horizontal and vertical greening systems entail certain drawbacks. The main challenge with horizontal greening systems is the high construction cost, which can vary based on location, labor costs, green roof type, and materials used [19]. Additionally, maintenance costs are high because regular maintenance is required to check for plant health, drainage, and substrate in order to extend the life of the green roof [19]. Another significant drawback is the risk of roof leakage, which can limit widespread application. The predominant use of polymer materials for green roof components also hinders their environmental performance [20].

Regarding vertical greening systems, both LWS and GF entail additional expenses for construction and maintenance. The main cost when constructing the LWS is the irrigation pipe system that should be installed for supplying the plants' water needs along with the planter boxes attached to the surface, while the main expenses for GF are the auxiliary frames [21]. The maintenance costs may include expenses related to damages and issues with the irrigation system or auxiliary frame, as well as damage to the building facade caused by water and nutrient leakage [22]. Additionally, costs may arise from the supply of nutrients and the replacement of dead plants [16], [21], [22]. When considering the implementation of vertical greening systems, the aforementioned costs become a significant drawback [23], [24]. Additionally, most vertical greening systems exhibit low integration between the structure and the living organisms. At the same time, the materials used for the auxiliary frames have shorter longevity compared to the buildings themselves [5]. Vertical greening systems have been found to generate high environmental costs compared with bare walls, particularly when indirect systems with frames and felt layers are used due to the additional materials required [25]. These environmental costs refer to the impact of the production, use, maintenance, and disposal of different types of vertical greening systems, assessed across various environmental categories as defined by the Life Cycle Assessment (LCA).

Finally, watering is identified as another environmental burden, considering the liters of water required for the survival of the plant species for both vertical and horizontal greening systems [26].

The performance of horizontal and vertical greening systems varies significantly depending on the specific circumstances, making it challenging to draw direct comparisons. Predicting the impact of system characteristics on costs and benefits, along with estimating the influence of factors like building layout, climate conditions, and the urban environment, is difficult in relation to their benefits and costs [27]. Both greening systems face limitations related to costs, technical design challenges, and maintenance, which hinder their widespread application.

1.2. Problem statement

Bioreceptive materials

In order to tackle the aforementioned drawbacks, limitations, and technical difficulties associated with both vertical and horizontal greening systems, a new method for greening the building envelope is being studied. This method involves growing plants, both vascular and non-vascular, directly in building materials known as bioreceptive and hybrid materials, proposing a new alternative for vertical greening systems. According to Guillitte [28], bioreceptivity is defined as ”the aptitude of a material to be colonised by one or several groups of living organisms without necessarily undergoing any biodeterioration.” The material primarily explored in the existing literature is concrete, recognized as the predominant construction material in urban environments [6], [29]. Moreover, organisms over time, naturally inhabit concrete, making it a potentially bioreceptive construction material since its mineralogical nature seems suitable for the growth of at least some organisms [30], [31]. Making concrete bioreceptive is a new research challenge that can help mitigate the environmental problems caused by increased urbanization in the cities. It can provide cities with a better living environment by reducing the UHI effect, air pollution, and increasing biodiversity and insulation properties [31]. Using the concrete’s building surface itself can offer these advantages without the need for additional materials for making auxiliary frames or planter boxes, lowering the installation and environmental costs [6]. Bioreceptive concrete can be classified into three types [31]:

- marine concrete: designed for use in marine environments such as underwater or intertidal zones [32], [33]
- traditional concrete: suitable for use in terrestrial settings [5], [4], [34], [35], [36], and
- permeable or highly porous concrete: it is used mostly in terrestrial settings. It has greater porosity, is water-permeable, and a growing substrate is incorporated into the concrete product [6], [37], [38], [39], [40], [41], [42].

When discussing urban environments such as cities, the last two types of bioreceptive concrete are more relevant as they are used in a terrestrial setting. The second type of bioreceptive concrete, among those previously discussed, supports plant growth on the concrete itself. However, a significant challenge in this type of bioreceptive concrete is the concrete’s ability to retain water, necessary for plant growth. To address this issue, modifications have been made to the concrete mix, such as increasing the surface roughness of the concrete [4], [34] using a binder with lower pH than Ordinary Portland Cement (OPC) [36], [43], increasing the aggregate porosity, or changing the aggregate type to one with a higher water retention capacity [31], [34], [43]. The third type of bioreceptive concrete differs from the second type primarily in its porosity, which is accompanied by differences in aggregate packing and a reduced binder-to-aggregate ratio. Increased porosity in this type of concrete is also linked to high permeability, allowing water to move more easily through the concrete pores [44]. Typically, the void content ranges between 15% and 35% and the compressive strength from 2.8 to 28 MPa [41], [45]. When porosity increases, compressive strength has been observed to decrease and vice versa [46], [47]. Another important characteristic of this type of bioreceptive concrete is that the large pores can be filled with a growing substrate composed mostly of soil with added nutrients to support vascular plant growth [6], [42], [41]. The substrate is not anymore the concrete itself but the growing substrate that is incorporated in the voids of the porous concrete. Finally, the accommodation of vascular plants has been proven feasible in the literature, and quicker germination results have been observed compared to non-vascular plants [6], [40], [42]. As a result, porous concrete can be a promising bioreceptive concrete type in the terrestrial environment to be introduced in the building envelope of the cities.

Sustainable materials

After realizing that bioreceptive materials could have a positive impact on the city’s environment and help reduce environmental challenges, it is important to also focus on sustainable materials. This is because concrete, identified as a potential and most researched bioreceptive material, is a high-emission product, mainly due to cement production, which is responsible for approximately 7% of global greenhouse gas emissions (GHG) [48].

When referring to sustainable materials, it is important to define the term ”sustainability performance.” Due to the lack of consistent definitions in the literature [49], defining and measuring sustainability is challenging, as the concept is complex, contextual, and dynamic. In this research, ”strong sustainability” is the focus, prioritizing the environmental perspective as the primary concern, followed by social and economic considerations.

In the context of urban environments, the environmental performance of materials is emphasized, including their extraction processes, associated emissions, life expectancy, and disposal scenarios. The challenges of climate change, the scarcity of natural resources, and the availability of waste materials that can be reused or recycled highlight the importance of making urban structures more sustainable. To achieve this, building envelope materials should be replaced with environmentally friendly alternatives that fulfill their intended function while minimizing environmental impact. This approach aligns with the framework for strong sustainability proposed by de Oliveira Neto et al. [50], as illustrated in Figure 1.3.

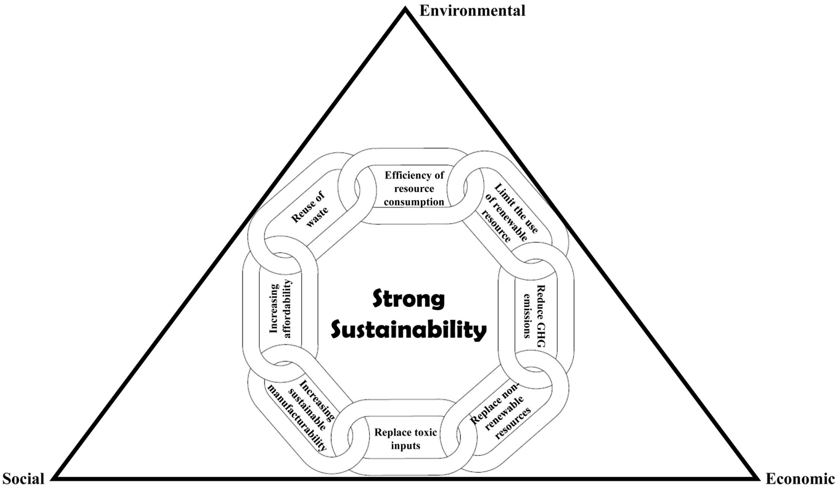


Figure 1.3: Final framework with eight specific actions to promote strong sustainability as defined by de Oliveira Neto [50] (acquired from [50]).

Regulations requiring the use of sustainable materials in the city's envelope are already in effect. Specifically, the United Nations, through the Sustainable Development Goals (SDGs) [51], have identified SDG 11 as the goal for "Making cities and human settlements inclusive, safe, resilient, and sustainable." Furthermore, the European Union has set goals that include adapting to climate change and achieving 100 climate-neutral and smart cities by 2030 [52]. To accurately assess the sustainability performance of a material, Life Cycle Assessment (LCA) is employed as a key environmental management tool. LCA evaluates the environmental impacts and burdens of a product or service by quantifying material and energy consumption, as well as waste generation, throughout its entire lifespan. While LCA primarily focuses on environmental aspects, its comprehensive life cycle approach can also be adapted to address economic and social impacts [53].

Outcome
For mitigating the environmental problems in the city's environment, it is important to consider both bioreceptivity and sustainability in the city's structure as already introduced. Porous concrete has been identified as a promising material for the terrestrial environment of cities due to its bioreceptive properties. When using porous concrete, it is important to consider its lower compressive strength, which makes it most suitable for non-load-bearing structures. One question to consider is whether the final mix design can be used to create a single porous layer wall, or if a two-layer structure is necessary to provide structural integrity. The compressive strength results will dictate the final application of the porous concrete, potentially leading to two different infrastructure applications in the city.

- One porous layer: Based on the authors' knowledge, porous concrete has not been used in single-layer wall structures to date due to its low compressive strength. However, if compressive strength requirements are met, there are potential applications for bioreceptive porous concrete. In the Netherlands, there is an opportunity to implement bioreceptive concrete in bicycle infrastructure. Dutch cities have specialized infrastructure, such as cyclist bridges and underpasses, designed to separate bicycle traffic from motor vehicles [54, 55, 56]. Underpass bicycle walls act as soil supports within the bicycle infrastructure and have the potential to be self-sufficient in terms of irrigation. These walls can access soil, nutrients, and water from the structure's rear facade, which helps supply the necessary water and nutrients to the growing substrate within the concrete pores. Due to their role as soil supports and their lower load-bearing requirements, underpass bicycle walls present an ideal opportunity to introduce bioreceptive and sustainable concrete wall structures. However, the exact number of underpass bicycle walls is not reported. Implementing bioreceptive and sustainable walls should be more widespread in non-load-bearing wall structures within the building envelope. Significant alternatives include noise barrier walls used on highways.

- Two-layer structure: In the literature, the two-layer structure is the most commonly researched application of bioreceptive porous concrete [38], [39], [6]. Due to the low compressive strength of porous concrete, a backing structure is typically used to provide structural integrity, while the surface layer serves as the bioreceptive component. Structural integrity, in this context, refers to ensuring the strength, stiffness, and anchorage necessary to support the living wall assembly. The two-layer structure has broader potential applications, as compressive strength is not a limiting factor, making it suitable for being used as an alternative for vertical greening systems.

Consequently, the primary research objective of this thesis is to develop a bioreceptive and sustainable concrete mix design for vertical greening systems in the Netherlands.

1.3. Research questions

Following Subchapter 1.2, this thesis aims to address the main research question (RQ) described below:

How can the concrete mix design of vertical greening systems be modified to be both bioreceptive and sustainable while maintaining sufficient structural integrity in terms of compressive strength and freeze-thaw resistance?

To reply to the main question, sub-questions are being formulated.

- **SQ1:** How should the concrete mix design be changed on the material level to satisfy all three design criteria of bioreceptivity, sustainability, and sufficient structural integrity?
- **SQ2:** How can the growing substrate be incorporated into the concrete mix, ensuring its adequate distribution within the pores of the porous concrete to enable testing for bioreceptivity?
- **SQ3:** Which proposed changes in the mix design contribute to satisfying the three design criteria?

1.4. Approach and reading guide

The full approach in the form of execution steps can be found below.

Step 1: Literature review: The first step is the literature review on bioreceptive porous mix designs to identify the properties that influence bioreceptivity in a concrete mix design. This involves investigating the previous applications of porous concrete mix designs in the building envelope and understanding the gaps and limitations in the existing research. This step is achieved through a literature review and provides a foundational basis for proceeding to the second step of the methodology while serves as a reference material for answering SQ1.

Step 2: Material selection: The second step involves selecting the appropriate materials for developing a sustainable and bioreceptive concrete mix design. To identify a concrete mix design that ensures both bioreceptivity and sustainability, a multi-criteria analysis is conducted for the materials used in the mix, specifically the binder and aggregates. This analysis is based on properties identified as important for achieving these objectives. During this step, factors such as current industry practices and anticipated future changes in the binder industry are taken into account, along with identified gaps in the literature. These gaps refer to the lack of investigation into certain binder and aggregate alternatives. All of these considerations guide the selection of the final concrete mix designs, providing a final answer for SQ1.

Step 3: The used methodology: Before the mix designs are developed, the methodology used in this research should be understood. The method employed in this research is the iterative process (Figure 1.4). This involves defining the research problem, conducting a literature review, formulating hypotheses based on research objectives, conducting preliminary testing, analyzing and interpreting the results, and refining hypotheses with further testing if needed.

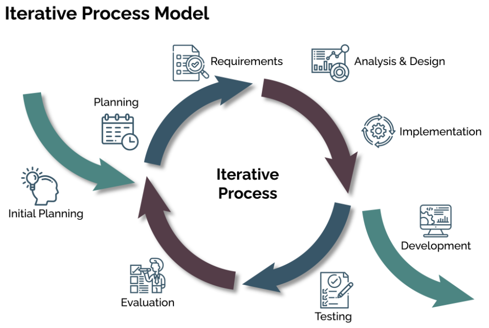


Figure 1.4: Iterative process model

In this research, the ratios of binder, water, and additives in the concrete mix designs are specified using an iterative process that is applied after the materials are chosen for the mix designs. As presented in Figure 1.5 below, the volumetric contents of materials are chosen based on literature review and EU guidelines. Concrete mortars are made to test the compressive strength after 5 days of curing and observe the interconnected porosity, workability of the mix, and demoulding outcome. After interpreting the results, if the chosen ratios do not yield the desired outcomes, different ratios are tested, and the process is repeated until the results are satisfactory. Once the optimal volumetric proportions are found, concrete samples are cast to test the final properties in terms of structural integrity, bioreceptivity, and sustainability. Conclusions are drawn after these experiments. If the concrete mix designs developed do not meet the three design criteria requirements, the process restarts, going back to the material selection phase, until the requirements are met and the optimal mix design is found.

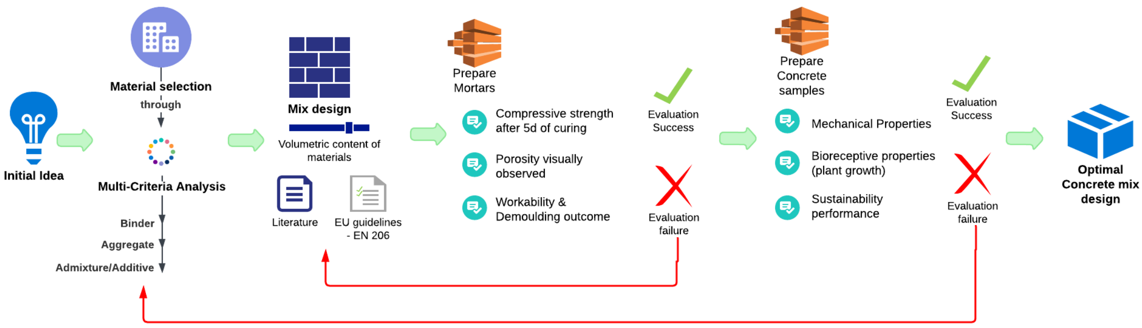


Figure 1.5: Iterative process used as research methodology.

Step 4: Experimental set-up: In this step, the experimental setup for testing the concrete samples mix designs on various properties, including mechanical and bioreceptive characteristics, are introduced.

For mechanical properties, tests such as compressive strength and freeze-thaw resistance are conducted. In terms of bioreceptive properties, two crucial steps are involved. The first step involves incorporating the growing substrate into the porous concrete, addressing a gap in the literature, and answering SQ2 through testing. Once the optimal incorporation method is identified, the second step involves conducting tests to measure water absorption and retention with and without the substrate, and porosity of the concrete product. The alkalinity of the concrete and substrate, as well as their interaction, is also calculated. Finally, samples incorporating the growing substrate undergo bioreceptivity testing, assessing plant growth over one month in the TU Delft Hortus Botanicus.

Step 5: Experimental results: This section presents the experimental results. It includes the mechanical and bioreceptive properties of the concrete samples, and the best method for incorporating the growing substrate in the cube samples. Additionally, it contains the plant growth results for each mix design tested. The results, interpretations, and concise conclusions for all properties tested are provided.

Step 6: Life cycle assessment of concrete mix designs: After selecting materials based on their sustainability performance—considering CO_2 emissions from binder production and emissions from aggregate extraction, along with economic allocation impacts where applicable—the sustainability of these materials is further validated through a Life Cycle Assessment (LCA). LCA is one of the most widely used environmental management tools for assessing the impacts and environmental loadings of a product, focusing primarily on environmental sustainability. Using this approach, the shadow costs of the concrete products are calculated according to the European standards NEN-EN 14044 and NEN-EN 15804+A1. The LCA evaluates the production of 1m^3 of concrete, addressing SQ3 by providing insights into the sustainability of the concrete product.

Step 7: Conclude the report: The final step involves discussing and identifying the optimal mix design that meets the three design criteria introduced in the main research question. The report's final conclusions are presented, along with recommendations for future research.

The reading guide, which links the approach steps to the chapters and research questions, is presented in Figure 1.6 below.

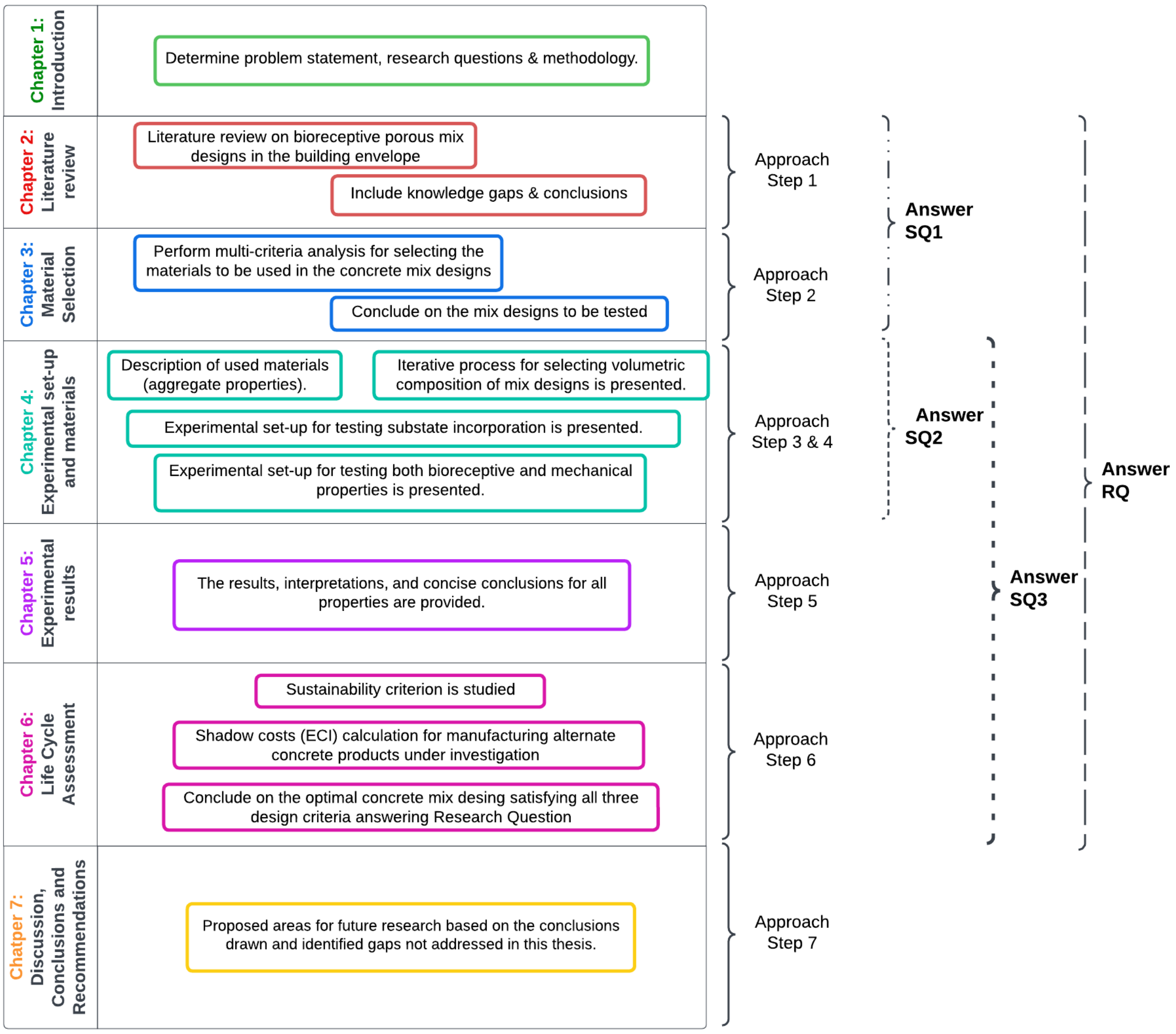


Figure 1.6: Reading guide

2

Literature review

This chapter presents the literature review in a structured manner. In Section 2.1, the concept of bioreceptivity in concrete is further elaborated for complementary purposes. In Section 2.2, the design requirements for obtaining bioreceptive porous concrete are discussed. In Sections 2.3 and 2.4, the use of bioreceptive porous concrete in the building envelope and for vegetation purposes is presented respectively. Finally, Section 2.5 concludes the literature review and summarizes the knowledge gaps as identified in the existing literature for bioreceptive porous concrete.

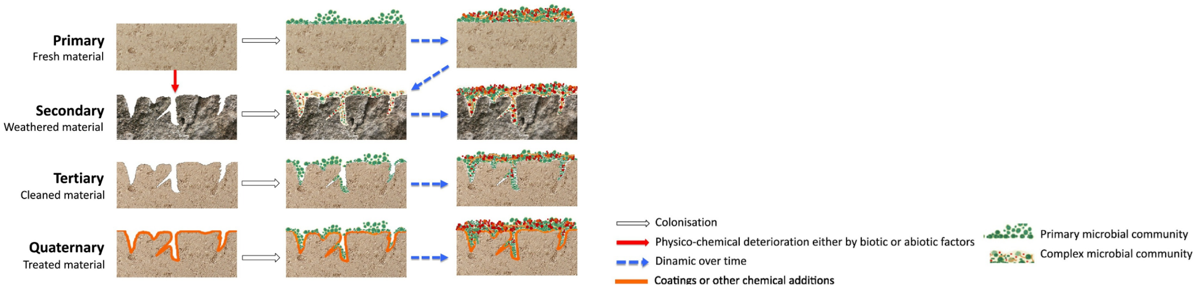
2.1. Introduction to concrete bioreceptivity

2.1.1. Types of Bioreceptivity

Bioreceptivity, as a term, has already been defined in Chapter 1 (Section 1.2). It is distinguished into different types, defined by Guillette [28] in 1995 and elaborated by Sanmartin, et al. [57] in 2020. The improved terminologies by Sanmartin, et al. [57] are presented to distinguish between the various types of bioreceptivity, namely primary, secondary, tertiary, and quaternary, and the intrinsic and extrinsic factors affecting bioreceptivity.

Primary bioreceptivity suggests that the material is conducive to biological colonization or growth after being manipulated for its final function. Secondary bioreceptivity indicates that the material becomes bioreceptive after weathering by environmental factors. Tertiary and quaternary bioreceptivity types refer to materials' bioreceptivity after being altered due to human activity. The difference is that the former relates to properties changed due to mechanical cleaning and the latter to changes due to the permanent or semi-permanent integration of chemicals into the original material [31], [57]. Finally, a distinction is made between intrinsic and extrinsic factors that stimulate bioreceptivity. Intrinsic factors relate to characteristics inherent within the material, while extrinsic factors refer to external factors that affect bioreceptivity [57].

In Figure 2.1, the different types of bioreceptivity as defined by Sanmartin, et al. [57] are presented.



(a) Types of bioreceptivity

(b) Brief explanation

Figure 2.1: Types of bioreceptivity as defined by Sanmartin [57] (acquired from [57]).

2.1.2. Concrete bioreceptivity

Concrete has emerged as a promising bioreceptive material, as it has been observed to be colonized by organisms over time, making secondary bioreceptivity feasible [31]. Concerning concrete, there are three categories of bioreceptivity as defined in Chapter 1 (Section 1.2). Each type of bioreceptive concrete has distinct requirements and finds application in different context.

Marine concrete is applied in marine environments, either underwater or in intertidal zones [31]. The advantage of this type of concrete lies in its constant water exposure. The primary factors influencing bioreceptivity in marine concrete are surface roughness and the application of surface patterns, which can create various microhabitats on the concrete surface [31]. Additionally, replacing Ordinary Portland Cement (OPC) with Ground Granulated Blast Furnace Slag (GBFS) has been found to reduce the alkalinity of the concrete substrate and improve bioreceptivity [31]. Based on the persistence of their significant effect, the intrinsic parameters that support greater biocolonization are classified from more to less effective in the following order: surface design (roughness) > chemical composition (slag cement CEM III) > patterned surface > chemical characteristics (ex. formwork oil) [58]. Another parameter that improves bioreceptivity in the marine environment is the utilization of highly porous or foamed concrete, where algae concentration appears to be higher compared to non-foamed or denser surfaces [59], [60].

Terrestrial concrete is predominantly used in engineering structures within urban environments. The primary challenge faced with this type of concrete is the limited availability of water for plant growth [31]. Various measures have been explored to enhance water retention in terrestrial concrete. Methods to improve its bioreceptivity include incorporating porous aggregates and fillers, as well as altering the surface texture to a rougher finish [31]. This facilitates the establishment and survival of microorganisms by providing protected microhabitats. At the same time, surface pattern is found to be advantageous for bioreceptivity as it is directing the water flow and can be used to control where growth occurs [61], [4]. Using a non-optimal aggregate by employing a coarser aggregate has also been found to improve bioreceptivity, likely due to the increased porosity this causes in the overall concrete structure [62]. Other modifications attempted, but with ambivalent results according to different researches, include increasing the water-cement factor (wcf) [34] and changing the chemical composition of the binder. The latest involves modifying ordinary Portland cement (OPC), the most commonly used type of binder, by adding additives to reduce its alkalinity (surface pH), such as lime trass [43], or studying alternative binders like Magnesium Phosphate Cement (MPC) [4], [36], [12].

Finally, porous concrete is characterized by its increased void ratio affecting the macro-pores of the concrete product, decreased binder content, and non-optimal aggregate packing [63]. The bioreceptivity of porous concrete is influenced by external factors. Unlike other types of bioreceptive concrete, porous concrete contains a growing substrate made of potting soil and nutrients. This means that the bioreceptivity is not solely dependent on the concrete substrate itself, but also on the design of porous concrete that increases the void ratio and incorporates a growing substrate inside the pores of the concrete. Certain design criteria must be followed to achieve bioreceptive porous concrete. These criteria are elaborated on in Section 2.2.

In Table 2.1 below, the different types of concrete bioreceptivity are presented with the most important properties that influence their bioreceptivity performance according to literature studied.

Table 2.1: Key properties of bioreceptive concrete.

Concrete Bioreceptivity	Main application	Primary properties affecting bioreceptivity	
Marine concrete	Underwater/ Intertidal zones	Surface Texture	Increase surface roughness Incorporate surface pattern
		Chemical Composition	Replace OPC with GBFS (lower surface pH)
		Porosity	Use highly porous or foamed concrete
Terrestrial concrete	Terrestrial environment	Surface Texture	Increase surface roughness Incorporate surface pattern
		Porosity	Incorporate porous aggregate or filler Employing coarser aggregate
Porous/Permeable concrete	Terrestrial environment	Design criteria	Increase void ratio, interconnected pores & macro-pores Modify aggregate gradation Decrease binder content Incorporate growing substrate

As discussed in Chapter 1 (Section 1.2), porous concrete has been identified as a promising type of bioreceptive concrete for integration into the urban building envelope. Its high interconnected porosity and increased water permeability positively affect water accessibility for plants within the concrete. The incorporation of a soil substrate provides a soil based environment for the plants to growth other than that of the concrete substrate, offering a familiar medium for the plants to germinate. From this point forward, the focus on bioreceptive concrete is on the introduced porous concrete type.

2.2. Porous concrete bioreceptivity design requirements

To create a concrete mix that is bioreceptive, certain design criteria need to be considered. The most important physical design requirements include having a pore size that is large enough to accommodate the growing substrate, allowing the roots to interconnect, and facilitating easy movement of water and nutrients between the pores of the concrete [40]. Although bioreceptive porous concrete does not have a standard mix design procedure, literature suggests considering various parameters to meet specific design criteria [64].

2.2.1. Aggregate size and gradation

The main difference between porous concrete and traditional concrete is that porous concrete has a higher void ratio, which ranges from 15% to 35% [64, 40]. This increased void ratio is achieved by using coarse aggregate and eliminating the use of fine aggregates [63]. The size of the coarse aggregates used is critical in creating enough voids in the final concrete product. Studies have shown that the particle sizes can range between 4.5 to 20 mm [46]. As the aggregate size increases, porosity increases, but compressive strength tends to decrease [65]. Additionally, aggregate gradation changes in porous concrete mixes. While single-sized aggregates are preferable to increase the void ratio and permeability of the final concrete product, they often result in decreased compressive strength and durability [63]. Studies suggest that employing various fractions of coarse aggregates, rather than a single fraction, can increase the compressive strength of porous concrete [66].

2.2.2. Binder content

The binder in a concrete mix plays an important role in binding the aggregates together. In porous concrete mixes, the binder content is decreased compared to traditional concrete mix designs to avoid negatively affecting the porosity of the concrete mix [40]. As the binder content decreases, the volume of aggregate increases and the aggregate-to-binder ratio also increases. This leads to lower compressive strength and increased porosity [46].

2.2.3. Water to binder ratio

The water-to-binder ratio typically ranges between 0.27 to 0.43 to achieve the desired workability of a porous concrete mix [64]. Workability refers to the characteristic of freshly mixed mortar or concrete that determines how easily and uniformly it can be mixed, applied, consolidated, and finished [67]. Studies have shown that increasing the water-to-binder ratio from 0.3 to 0.4 can result in higher compressive strength. However, this is further affected by the shape of the aggregate (angular or irregular), the size of the aggregate, and different percentage increases in compressive strength have been observed. An average compressive strength of approximately 10 MPa was observed for a common porous concrete product with a water-to-binder ratio of 0.4, using Ordinary Portland Cement (OPC) and natural aggregates sized 6-10 mm [45], [46], [65].

2.2.4. Growing substrate

It is worth noting that bioreceptive porous concrete offers an additional potential benefit beyond its design requirements: it can incorporate a soil-based growing substrate within its pores, providing a familiar medium for plants to thrive, instead of the concrete substrate. The incorporation of the substrate is linked to the void ratio and porosity of the concrete product. It is estimated that the higher the porosity, the easier the substrate incorporation.

2.2.5. Alkalinity processes

For porous concrete, the alkalinity of the binder does not restrict plant growth, as the concrete itself is not the substrate for the plants. Instead, the soil substrate added to the pores of the concrete serves as the growing medium, with a pH appropriate for plant growth. However, the leaching of compounds from the cement-based layer can potentially affect the final pH and alkalinity of the growing environment, possibly increasing the pH of the soil substrate [68].

In addition to the leaching of compounds, natural carbonation also occurs. Atmospheric CO_2 interacts with

$CaCO_3$ in the cement pore solution through a process known as carbonation, the rate of which depends on the environmental conditions to which the concrete is exposed [69]. This interaction reduces the superficial alkalinity of the concrete matrix [6].

Overall, two different mechanisms are associated with alkalinity changes: leaching of elements from the concrete substrate, which can increase the pH of the growing substrate, and carbonation of the concrete surface, which decreases the pH of the concrete substrate.

2.2.6. Conclusions on design requirements

Table 2.2 summarizes the requirements for obtaining a bioreceptive porous concrete.

Table 2.2: Design requirement for bioreceptive porous concrete.

Design requirement	Number range	Description	Positive effect	Negative effect	Source
Void ratio	15%-35%				[64, 40]
Aggregate size	4.5 - 20 mm	Higher aggregate size	Increase porosity	Decrease compressive strength	[46], [65]
Aggregate gradation		Single-sized aggregates	Increase void ratio & permeability	Decrease compressive strength	[65]
		Various fractions of coarse aggregates	Increase compressive strength		[66]
Binder content & Aggregate-to-binder ratio (abr)		Decrease binder content	Increase abr & porosity & permeability	Decrease compressive strength	[45], [46],[65]
Growing substrate		This is not a design criterion but affected by porosity, aggregate size & gradation			

2.3. Bioreceptive porous concrete in the building envelope

2.3.1. Introduction

Research on porous concrete in the building envelope, particularly concerning wall structures, is still in its early stages. Most studies focus on vegetation porous concrete, a type used for slope and riverbank protection. The main difference lies in the soil incorporation, which is poured onto the top of the porous concrete rather than being integrated into its pores. Previous research on vegetation porous concrete has investigated mechanical, physical, and bioreceptive properties such as compressive strength, porosity, permeability, and plant growth, providing crucial insights for the implementation of porous concrete in the building envelope. Consequently, relevant findings from studies on vegetation porous concrete are also considered in the literature review.

2.3.2. Literature findings

Riley, et al. [6] studied three porous concrete mix designs: pure cement (OPC), cement with metakaolin and limestone filler to lower pH, and the same mix with white cement for aesthetics. A two-layer wall structure was proposed with pervious concrete as the surface bioreceptive layer for plant growth and a steel-reinforced concrete backing layer for support (Figure 2.2).

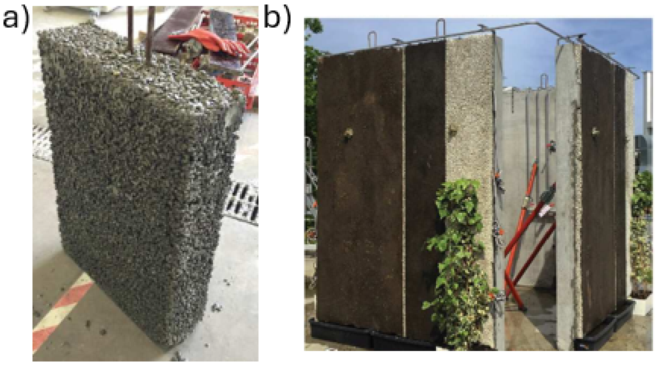


Figure 2.2: Two-layer wall structure a) Mini-wall validated construction methodology and mix design b) full-size construction with seeded substrate completed as studied by Riley, et al. [6].

Aggregates ranged from 6-10 mm, and a superplasticizer was used in the mix. The growing medium, including seeds, soil, and compost, was integrated into the concrete pores. Plant species were selected based on soil tolerance and root diameter. Outdoor germination testing after full-size construction revealed that metakaolin use was unnecessary, as natural carbonation quickly lowered surface pH. An irrigation system was also installed to supply plants with water during the outdoor germination tests. Living wall mechanical properties revealed that the 28-day compressive strength reached 10 MPa with porosity close to 32%.

Jakubovskis, et al. [38] investigated bio-colonisation of a layered concrete panel. The research involved a two-layer structure with a bioreceptive surface layer and a high-strength fiber-reinforced concrete backing layer. Various mixes for the porous bioreceptive layer were tested, using expanded clay aggregates (2/4mm, 4/8 mm, 8/16 mm) for their high water absorption properties. The binder included cement, nano-silica, and a spent catalyst. Superplasticizer was also added to the mix. All mixes exhibited high water infiltration rates with varying compressive strengths as presented in Figure 2.3. A bio-booster made from forest topsoil and recycled paper pulp was glued on the wall surface to serve as a water-retaining substrate and enhanced plant growth in outdoor testing.

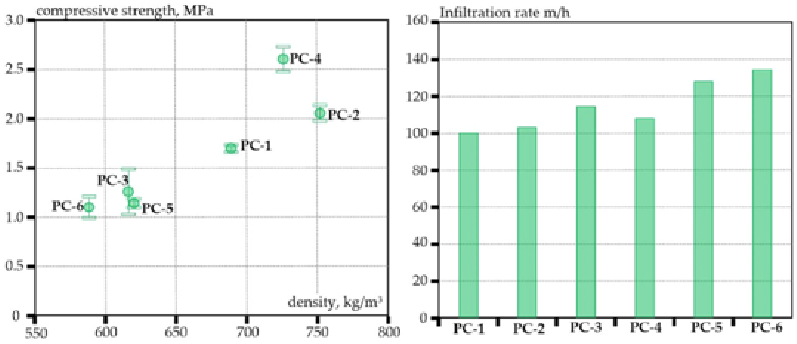


Figure 2.3: Compressive strength and Infiltration rate results on the porous mix designs studied by Jakubovskis, et al. [38].

Zhao, et al. [42] investigated the Magnesium ammonium phosphate cement (MPC) to lower the alkalinity of concrete for plant growth. Aggregates used were crushed stone (19/26.5 mm). Various mix modifications were explored, including phosphate-to-magnesium ratio (P/M), borax content, water-to-binder ratio (W/B), and addition of fly ash (FA) and blast furnace slag (GBFS). The most suitable mix (P/M = 1/4, GBFS = 20%) in terms of alkalinity (Figure 2.4 a), compressive strength (Figure 2.4 b), and pore structure was utilized to create porous ecological concrete based on MPC for testing plant germination.

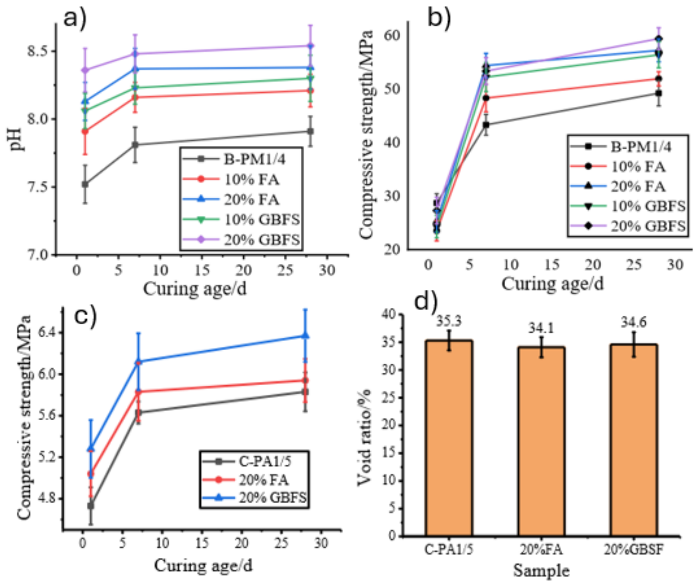


Figure 2.4: Effect of mineral admixtures on a) alkalinity of MPC, b) compressive strength of MPC, c) compressive strength of porous ecological concrete and d) void ratio of porous ecological concrete [42].

It was observed that the designed porous mix facilitated rapid germination, with a soil substrate incorporated into its pores. It was concluded that despite promising results in enhancing compressive strength and bioreceptive characteristics, the cost of MPC-based ecological concrete remains a significant obstacle.

Hitti, et al. [40] developed a new porous concrete substrate for agricultural plant growth. The geopolymer concrete proposed was made from GBFS to adjust substrate pH for healthier root development while minimizing alkali activator content to prevent plant damage. Geopolymer formation occurred with quartz aggregates (2/3.2mm), and a 30% void content was maintained for optimal permeability within legal constraints. The W/B ratio was set at 0.295. Germination trials involving tomato, radish, and romaine lettuce seeds were treated with Hoagland nutrient solutions in different proportions. However, the exploration of geopolymer's viability in the wall structures was not the subject of this study, limiting its relevance beyond hydroponic systems.

In the following Table 2.3 the outcomes and findings of the porous concrete use in the building envelope are being presented.

Table 2.3: Literature findings on porous concrete mix design.

Source	Bioreceptive porous concrete mix			Design & Bioreceptivity	Key findings & Limitations
	Binder	**Aggregate Gradation**	**Admixtures & Additives**		
[6]	1. OPC 2. OPC & Metakaolin 3. White OPC	Natural: 6/10mm	Superplasticizer	Two-layer wall structure with a structural concrete backing support. Growing substrate poured into the pores of concrete.	Metakaolin not needed for pH reduction. Outdoor carbonation was fast.
[38]	Cement, nano-silica, spent catalyst	Expanded clay: (2/4mm, 4/8 mm, 8/16 mm)	Superplasticizer	Two-layer wall structure. Growing substrate glued on the wall surface.	Expanded clay had high water absorption rates.
[41]	OPC	Natural: 20mm	FA	Growing substrate poured into the pores of concrete by mechanical vibration.	
[42]	MPC	Crushed stone: (19/26.5 mm)	FA GBFS	Growing substrate poured into the pores of concrete.	Cost of MPC
[40]	Geopolymer made from GBFS	Quartz (2/3.2mm)	Alkali activator	Hoagland nutrient solutions	Tested only in hydroponic systems, not for wall structures.

2.4. Vegetation porous concrete

2.4.1. Literature findings

Bao, et al. [37] explored the development of a porous concrete mix for soil-slope protection with reduced alkalinity and efficient mechanical properties. The incorporation of a self-designed admixture was investigated, mainly composed of silica fume, in varying proportions with OPC as the binder. Crushed limestone aggregates (19 mm) were used, resulting in a void ratio of 27% and a water-to-cement ratio of 0.35. Tests conducted on porosity, permeability, compressive strength, and elastic modulus revealed that increasing the admixture content reduced porosity while significantly enhancing compressive strength. For vegetation testing, a growing substrate layer (1-2 mm of nutrient soil) was applied to the concrete pores, followed by seed sowing. Germination began within one week of sowing, showing rapid growth.

Quan, et al. [70] studied the effects of aggregate sizes (5/10mm, 10/15mm, 15/20mm, 5/20 mm) and aggregate-to-cement ratio (6, 8) on compressive strength, permeability, and plant growth in concrete mixes. They used OPC binder with crushed limestone. Pores were filled with a mixture of peat moss, soil, fertilizer, and water, seeded with tall fescue. Results showed that aggregate gradation, cement content, and water-cement ratio influence concrete texture and its compatibility with plants. An aggregate-cement ratio of 8 and a water-cement ratio of approximately 0.35 were recommended for ecological concrete products appropriate for plant growth.

Zhuang, et al. [65] examined the effects of coarse aggregate size (5/15mm, 25/35mm, 15/25mm), porosity (25%, 30%), and water-to-cement ratio (0.25-0.4) on bioreceptive concrete properties. The mix comprised OPC, crushed limestone, and 10% fly ash (FA) replacing OPC. Larger aggregate size and higher porosity reduced compressive strength (Figure 2.5 a and c), while increasing water-to-cement ratio enhanced it (Figure 2.5 d) and lowered pH. Increasing the coarse aggregate size led to an increase in the measured porosity (Figure 2.5 b). The inclusion of FA decreased compressive strength without affecting pH. Tall fescue growth was observed after 7 days.

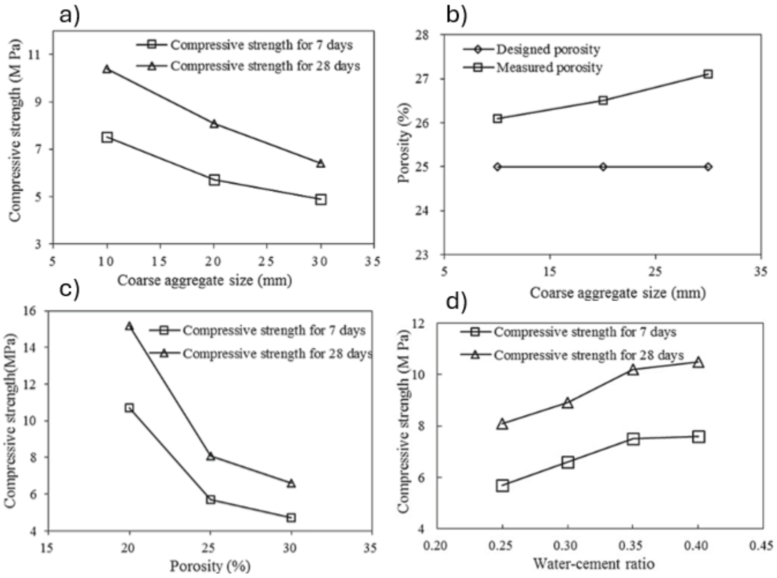


Figure 2.5: Effect of a) coarse aggregate size to compressive strength and b) on porosity, c) effect of porosity on compressive strength and d) effect of WCR to compressive strength as studied by Zhuang, et al. [65].

Kim, et al. [71] investigated incorporating GBFS binder (100% cement replacement) and (BFS) aggregates (40% NA replacement - 8/25mm), along with 0.1% jute fibers and 0.02% styrene butadiene (SB) latex by weight of the binder. The water-to-binder ratio was 0.26 and the aggregate-to-cement ratio was approximately 5 (4.6). Latex particles formed a film during cement hydration, enhancing bond and tensile strength by filling voids. The optimal mix where latex was included achieved compressive strength exceeding 13 MPa, a void ratio of 26%, the highest plant growth (Figure 2.6), and appropriate FT resistance compared with the target performance.

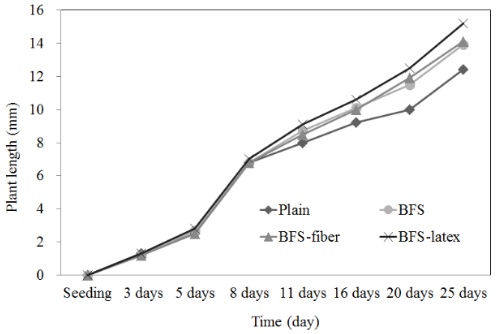


Figure 2.6: Plant growth as studied by Kim, et al. [71].

In a separate study, Kim, et al. [72] investigated the impact of BFS aggregates on compressive strength, void ratio, and freeze-thaw resistance. OPC cement with 60% BFS replacement was used to lower pH. Different proportions of BFS aggregates (0%, 20%, 40%, 60%, 80%, 100%) were incorporated, along with either natural jute fiber (0.1% of cement volume) or SB latex (5% of cement volume). The water-to-cement ratio was set to 0.27 and an aggregate-to-cement ratio to 4. Key findings revealed that even with 100% aggregate replacement, the void ratio remained above 25% across all mixes (Figure 2.7 a). Compressive strength decreased with increasing aggregate portion, but the incorporation of SB latex mitigated this decrease, approaching control mix levels (0% of BFS aggregates) as depicted in Figure 2.7 b. Furthermore, freeze-thaw resistance improved compared to the control with SB latex incorporation.

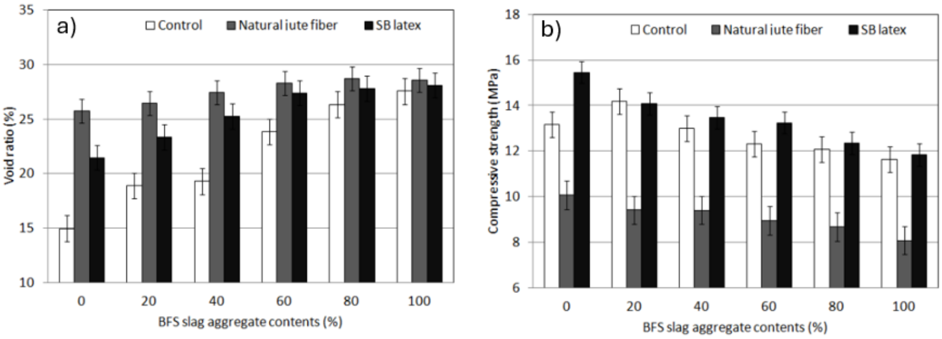


Figure 2.7: Effect of BFS aggregate content on void ratio and compressive strength as studied by Kim, et al. [72].

Chen, et al. [73] studied how aggregate size and water-to-cement ratio affect the mechanical and physical properties of planting concrete. They used OPC with limestone aggregates (10/30mm, 20/40mm) and water-to-cement ratios between 0.25 and 0.33. Results showed that increasing the water-to-cement ratio reduced porosity but increased compressive strength for both aggregate sizes. Tall fescue planted on the concrete surface began to germinate after 3 days.

Oh, et al. [74] studied mechanical properties and water purification of natural jute fiber-reinforced non-cement alkali-activated porous vegetation blocks. These blocks were made solely from blast furnace slag and sodium silicate mixed with an alkali activator (replacement 5% to 10% of binder weight), along with jute fiber (0.1%, 0.2% of binder weight). Coarse aggregates up to 25mm were used, with a water-to-cement ratio of 0.26 and aggregate-to-cement ratio close to 5. It was found that pH was minimally affected by jute fiber content but increased with alkali activator content. Both jute fiber and alkali activator content correlated with increased void ratio and compressive strength as presented in Figure 2.8.

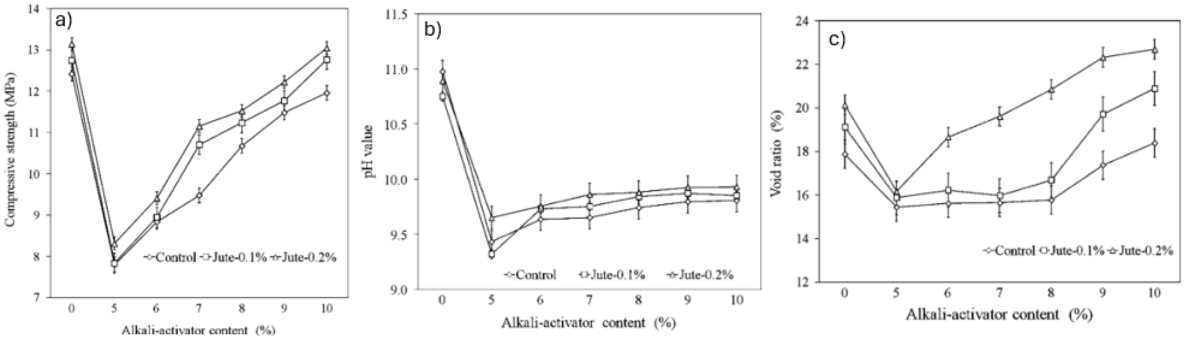


Figure 2.8: Results of natural jute fiber-reinforced non-cement alkali-activated porous vegetation blocks on a) compressive strength b) pH value and c) void ratio, as studied by Oh, et al. [74].

Mixes with 0.1% to 0.2% jute fiber and 9% alkali activator showed comparable or slightly lower compressive strengths than cement mixes. Although the mix made was for porous vegetation blocks, germination was not tested.

Tang, et al. [75] explored vegetation concrete development for slope protection using calcium aluminate cement (CAC) as an alternative binder to lower pH. Fly ash replaced CAC at volumes of 10%, 20%, and 30% with 20mm crushed gravel as coarse aggregate and a water-to-binder ratio of 0.4. The results showed that with an increase in FA content, compressive strength improved, peaking at 2 MPa, while porosity reached 37%. Grass seeds were sown and their germination was observed in a temperature-controlled glasshouse to standardize growth conditions. Only two grass species, Chloris truncata and Elymus scaber, were found to be compatible for use in vegetation porous concrete, even though all tested species had similar properties, including pH tolerance in alkaline environments and tolerance to high heat, frost, and drought.

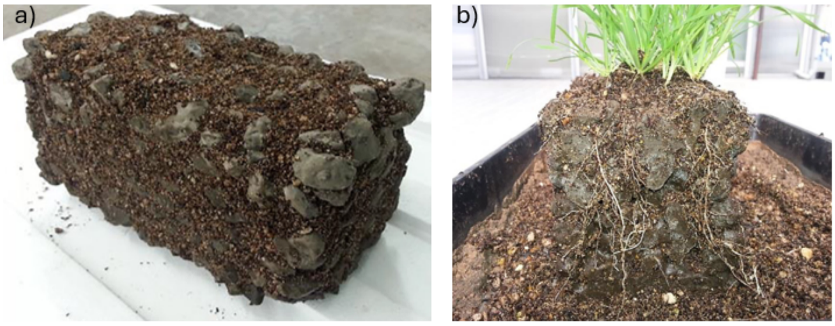


Figure 2.9: Vegetation porous concrete a) filled with soil into its pores and b) root development as depicted by Tang, et al. [75].

Wang, et al. [76] studied the impact of ultrafine slag incorporation at different cement substitution rates (0%, 20%, 40%, 60%, 80%) and the addition of recycled aggregates from concrete beams (5/25mm) with varying porosity (15-35%). It was found that as slag powder content and porosity increased, compressive strength decreased, influenced also by aggregate gradation and recycled aggregates, further reducing compressive strength. Additionally, higher water-to-cement ratios decreased compressive strength. The study also investigated the effect of plant growth on the mechanical properties of vegetation porous concrete. Concerning compressive strength, a negative effect was observed initially after the incorporation of the substrate, and plant growth, followed by recovery in compressive strength results (Figure 2.10a). The permeability coefficient was also examined after plant growth, resulting in lower values, indicating positive water retention for plant growth (Figure 2.10b). Freeze-thaw resistance was also studied through the effect of compressive strength on the porous concrete mix design. It was found that after freeze-thaw cycling, the compressive strength remained stable, indicating enhanced frost resistance with vegetation planting (Figure 2.10c).

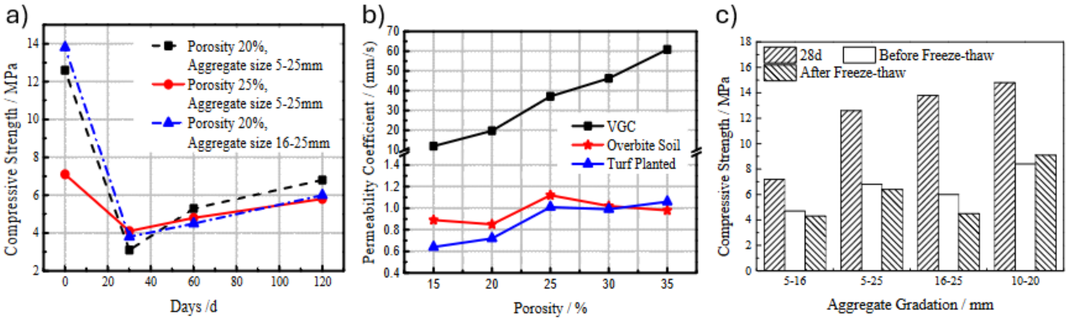


Figure 2.10: Effects of plant growth on a) compressive strength, b) permeability coefficient in different porosity and c) on freeze-thaw resistance in different aggregate gradation as studied by Wang, et al. [76].

Prabhu, et al. [77] investigated vegetation concrete compositions using river sand (2%), fly ash (FA substitution from 20% to 30%), silica fume (SF substitution from 6% to 12%), coarse aggregate (10/20mm), and regular OPC. Cement content remained constant and the water-cement ratio was set to 0.42 across all mixtures. Notable outcomes were the decrease in vegetation porous concrete (VPC) alkalinity due to FA and SF addition. Compressive strength decreased with increasing FA replacement due to poor binding with the cement matrix, while increasing SF replacement enhanced compressive strength. All mixtures exhibited satisfactory seed germination rates when compared to each other.

Gong, et al. [78] explored the effects of limestone powder incorporation in vegetation porous concrete using sulfoaluminate cement as a binder. Coarse aggregates ranged from 19.0 to 26.5 mm. Limestone powder proportion varied from 0% to 30%, in increments of 5%, with gypsum added to the binder to enhance strength and adjust setting time. Water-to-binder ratio was 0.2 and aggregate-to-binder ratio was 5. Findings revealed that up to 20% limestone powder replacement reduced alkalinity and increased water permeability, enhancing compressive strength to nearly 93 MPa. However, excessive limestone powder adversely affected fluidity and led to plant mortality, notably at 30% replacement.

In the following Table 2.4 the main findings from the literature on vegetation porous concrete are being presented.

Table 2.4: Literature findings on vegetation porous concrete.

Source	Vegetation porous concrete mix			Design & Bioreceptivity	Key findings & Limitations
	Binder	**Aggregate Gradation**	**Admixtures & Additives**		
[37]	OPC	Crushed limestone: 19mm	Self-designed: based on SF	Growing substrate layer: 1-2mm of nutrient soil	Rapid growth of Bahia grass
[70]	OPC	Crushed limestone: (5/10mm, 10/15mm, 15/20mm, 5/20mm)	None	Changing ABR (6, 8). Growing substrate poured in the pores of concrete.	Aggregate gradation, cement content & water content influence concrete texture and plant growth.
[65]	OPC	Crushed limestone: (5/15mm, 25/35mm, 15/25mm)	10% FA	Changing porosity (25,30%) & WBR (0.25-0.4)	Large aggregate size, high porosity & addition of FA decrease compressive strength. Increase of WBR, increases compressive strength. Germination of grass stared after 7 days.
[71]	GBFS	40% replacement with BFS aggregates: (8/25mm)	0.1% jute fibers & 0.02% SB latex by weight of binder	Grass seeds were sown in the surface of vegetation concrete blocks.	Incorporation of BFS aggregates & latex enhanced plant growth. Latex increased compressive strength.
[72]	OPC & 60% GBFS	Varying proportions of BFS: 0%-100%	0.1% jute fibers & 5% SB latex of cement volume	No plant growth testing	100% BFS aggregate replacement leads to void ratio above 25% with a decrease in compressive strength. Latex mitigates this decrease.
[73]	OPC	Limestone: (10/30mm, 20/40mm)	None	Grass seeds, soil, and water were spread by hand in the vegetation concrete blocks.	Increase of WBR, decrease porosity but increase compressive strength. Grass germinated after 3 days.
[74]	BFS & sodium silicate	Coarse: up to 25mm	Alkali activator (5% to 10% of binder weight) Jute fiber (0.1%, 0.2%)	Germination was not tested	pH increases by increase of alkali activator content. Jute fiber & activator increase void ratio & compressive strength.
[75]	CAC	Crushed gravel: 20mm	10%, 20%, 30% FA	Grass seeds sown in a temperature- controlled greenhouse. 3 species tested.	Increase FA content, improved compressive strength.
[76]	OPC, Ultrafine slag replacement (0% - 80%)	Recycled from concrete beams: 5/25mm	Water reducer	Varying porosity (15-35%). Soil incorporated into the pores of concrete & mechanical, physical properties were studied.	An increase in slag & porosity decreases compressive strength. Higher aggregate size, recycled aggregates & high WBR further decrease strength. After soil incorporation & plant growth, compressive strength decreased and then recovered.
[77]	OPC	Coarse: 10/20mm	2% river sand, 20% - 30% FA, 6%-12% SF		FA & SF decrease pH. FA decreases compressive strength due to poor binding with the cement matrix. Increase in SF, enhanced strength. All mixes had satisfactory germination rates.
[78]	CSA & 0%-30% limestone powders & 10-40% gypsum.	Coarse: 19/26.5mm	Water retarder		Up to 20% of limestone powder reduces pH and increases permeability and compressive strength.

2.5. Conclusions and Knowledge gaps

2.5.1. Conclusions

To conclude, various types of bioreceptive concrete have been identified: marine, terrestrial, and porous. The latter is mostly used for slope and riverbank protection. However, new research has focused on incorporating this type of bioreceptive concrete into the building envelope, especially in the wall structures, due to its positive impact on improving urban environments.

To summarize the various options tested for bioreceptive porous concrete products in the literature and their effects, a summary table (Table 2.5) is provided below, followed by a detailed analysis.

Table 2.5: Summary table for bioreceptive porous concrete.

Tested options for bioreceptive porous concrete	Description	Contribution effect	Comment
Binder			
Binder type	CAC MPC CSA	Decrease the pH of the concrete matrix. Reduce the use of OPC. Increased germination rates over OPC.	
Additive (SCMs)	GBFS, FA, SF	Decrease the pH of the concrete matrix, by reducing the use of OPC. Potential to decrease the environmental footprint of the concrete product.	Reduction of environmental footprint was not tested.
Binder content	Decreased	Increased void ratio & interconnected porosity of the concrete product.	
Aggregate			
Aggregate type	Natural, lightweight, by-products (BFS)	The use of lightweight showed higher porosity & water absorption rates but decreased compressive strength. The use of by-products (BFS) increased porosity and plant germination rate but decreased compressive strength.	Potentially can improve the water retention of the concrete product.
Aggregate gradation	Single-sized	Increase void ratio and permeability. Decrease compressive strength.	Various fractions of aggregates were suggested to improve the compressive strength.
Aggregate size	4.5 - 20 mm	Higher the size: higher the macroporosity & interconnected porosity, higher the water permeability. higher the available pore space for growing substrate incorporation.	
Admixture			
Admixture type	Superplasticizer	Most used admixture in all concrete products studied.	High amount of superplasticizer impacts negatively plant growth.
	SB latex	Increased plant growth & compressive strength.	
Plant properties			
Plant species	Alkaline environment Drought & heat resistance	Plant species studied were suitable for more alkaline environments, lead to positive germination results.	In wall structures, irrigation systems was structured for water supply.
Seeding technique	No requirement.	No specific proposals were made for the best seeding technique	
Alkalinity	Leaching phenomenon	Leaching from the concrete layer, increased the pH of the growing substrate but did not hinder germination.	
Incorporation method	Knowledge gap	No specific incorporation method was found. Pouring of the substrate in the concrete product was repeated in most of the studies.	
Design			
Two-layer structure	Structural integrity	Given the low compressive strength of the porous layer, a backing structural layer is made for structural integrity. Design geometries tested for incorporating plants in specified surfaces in the bioreceptive layer.	Most focus was given to vegetation porous concrete than in the city's environment.

Final conclusions based on the literature review

For obtaining bioreceptive porous concrete, specific design criteria should be considered, starting with aggregate gradation and larger aggregate sizes to enhance the void ratio of the concrete. The binder content is also decreased compared to traditional concrete, along with a water-to-binder ratio ranging between 0.27 and 0.43. Given these design criteria, the higher porosity decreases the compressive strength of porous concrete in wall structures, making the incorporation of a backing structure necessary to provide sufficient structural integrity according to strength requirements. In bioreceptive porous concrete, a growing substrate, often composed of potting soil, seeds, and nutrients, is incorporated into the pores of the concrete to create a suitable environment for plant growth.

In the various mix designs studied for bioreceptive porous concrete as identified in Section 2.3 and 2.4, different types of binders, including MPC, CSA, and CAC, were investigated to decrease the pH of the concrete substrate and potentially reduce the environmental footprint of the concrete product. However, there was no specific testing on sustainability properties to prove the potential decrease of the environmental footprint. The substitution of the OPC binder with GBFS and FA was also examined for the same reasons. It was found that incorporating GBFS further enhances plant growth due to its lower alkalinity compared with OPC. Regarding aggregate gradation and sizes, different types of aggregates were investigated for their physical and bioreceptive properties (such as water absorption, porosity, availability, and sustainability). Notable attention was given to how compressive strength is affected by high aggregate gradation and porosity, with compressive strength being the most important mechanical parameter studied in porous concrete products. It was found that increasing aggregate size decreased compressive strength while increasing porosity and water permeability. Additionally, incorporating different aggregate sizes resulted in higher strength compared with using only one aggregate size in the porous concrete products.

Finally, various seeding techniques and plant species were explored. No significant difference on plant germination was found between the seeding techniques (sowing seeds, gluing seeds on the surface, or stem cutting). The plant species used exhibited similar characteristics, being well-suited for thriving in alkaline environments and showing resistance to drought and heat.

2.5.2. Knowledge Gaps

Despite the research already conducted on bioreceptive porous concrete for use in both the building sector and vegetation purposes, various knowledge gaps remain and are addressed below.

- **Sustainability design:** None of the studies define the hidden costs at the product level or assess the sustainability performance of the final concrete product. The primary focus is on the material itself rather than on achieving a concrete product that is both bioreceptive and sustainable at the material level. Shadow costs for the production of the mix are not taken into account and investigated until now. When shadow costs are referred to, the Environmental Cost Indicator (ECI) of a product is considered, which is indicative of the damage that a product causes to the environment, expressed in monetary values (€).
- **Ability to apply without a backing structure:** The ability to create a self-supporting porous concrete mix -without a backing structure- for use in non-load-bearing vertical greening walls, has not yet been identified. While the application of a backing structure ensures the structural integrity of a wall, the self-supporting nature of these walls could offer advantages in terms of bioreceptivity and self-sufficiency, as defined in the following knowledge gap.
- **Ability to be made without irrigation system:** A related gap to the previous knowledge gap is whether bioreceptive porous concrete walls mostly in underpasses can be self-sufficient, meaning if they can function without the installation of an irrigation system, which would increase initial costs and maintenance expenses. This gap arises from the characteristic of underpass walls, where their backing structure facade comes into contact with the soil. Since they are used as soil supporters, they can potentially provide the growing substrate with the necessary water and nutrients.
- **Incorporation of the growing substrate in the pores:** The incorporation of the growing substrate into the pores of concrete is a missing element in the literature. In most studies, incorporation is not clearly defined, which poses a problem because porous concrete's enhanced porosity allows for the possible incorporation of a growing substrate, creating a conducive environment for plant growth.
- **Outdoor plant germination testing:** Bioreceptivity testing in outdoor conditions is limited in literature, as laboratory tests are preferred as they can generate faster results. This is mainly because outdoor testing can be affected by climate conditions and poses constraints in bioreceptive research.

Knowledge gaps to be addressed

In Figure 2.11 below, the knowledge gaps to be addressed are presented.

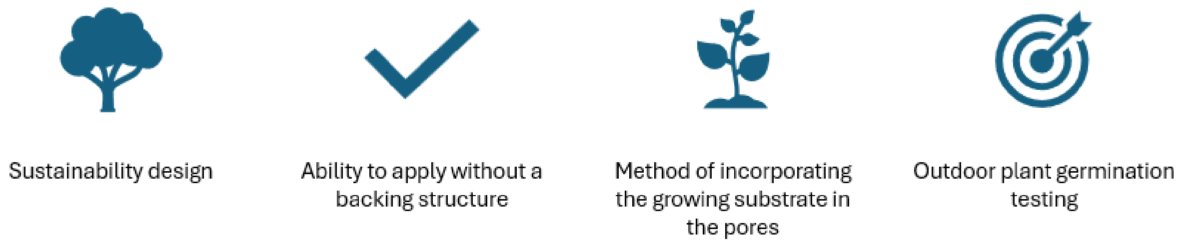


Figure 2.11: Knowledge gaps to be addressed.

Primarily, the sustainability design of the porous concrete product is investigated, identifying the shadow costs for manufacturing $1m^3$ of porous concrete. The incorporation of the growing substrate in the pores of porous concrete has not been thoroughly investigated and is not clearly defined in the literature, making it an important knowledge gap to be addressed. Since the growing substrate is incorporated in the pores of concrete, finding the most efficient method to distribute soil adequately within the pores of porous concrete is crucial. Finally, outdoor plant germination tests are conducted to measure real plant growth results in the concrete mix designs under investigation. Assessing the feasibility of constructing an underpass and/or non-load-bearing bioreceptive porous concrete wall without a backing structure and irrigation system cannot be fully determined based solely on mix design properties. Structural investigations and mock-up experiments are necessary to fill these knowledge gaps and could be explored further in another thesis. The primary discussion addressing these gaps is presented in the final concluding Chapter 7 in Section 7.1.6. However, the potential for implementing the concrete mix design without a backing structure can be evaluated by investigating the compressive strength of the concrete mix designs.

3

Material selection for mix design

In this chapter, the focus is on the selection process for the materials used in the concrete mix designs. It addresses the first research sub-question, which is: *How should the concrete mix design be changed on the material level to satisfy all three design criteria of bioreceptivity, sustainability, and sufficient structural integrity?*

Chapter 3 commences with a multi-criteria analysis for binder selection and outlines the final selection of binder in Section 3.2. Following this, the multi-criteria analysis for aggregate selection is presented, and the final selection for the aggregate type is documented in Section 3.3. The admixture selection is presented in Section 3.4 and Section 3.5 concludes on the final concrete mix designs.

3.1. Introduction

Various binder and aggregate materials are used in bioreceptive porous concrete for building envelopes or vegetation porous structures as described in Chapter 2. For the concrete mix design developed in this thesis, a range of binders and aggregates are considered as potential materials for the concrete mix design. Through the multi-criteria analysis, materials are compared and assessed for their bioreceptivity and sustainability performance, mechanical properties, and future demand in the concrete industry. Through the applied selection process, two different mix designs are chosen, as well as a reference mix design for comparisons between the different concrete products.

For both materials, mechanical properties that are taken into account in the selection process are compressive strength and freeze-thaw resistance. Compressive strength is important as the main mechanical property to characterize the concrete product and evaluate its use in an intended application. Freeze-thaw is also an important factor as it is one of the main durability factors of the concrete product and assess its performance in freeze-thaw cycles that can lead to deterioration of concrete through cracking and decrease its lifetime.

Regarding bioreceptivity, it is important to investigate the performance of the binder and the aggregate type in plant growth. The pH of the growing substrate can be affected by the leaching of the binder elements. Porosity and water absorption of aggregates can also impact plant growth. The possibility of plant growth is illustrated by the germination of the plants in the growing substrate of the concrete product, however, comparisons are difficult to make given that no standardized procedure exists for determining the plant growth success.

Sustainability performance is adversely affected by both the binder and aggregate used in concrete production due to the sourcing of materials and the processes required before they can be used (transportation and manufacturing stage). Initially, the selection process for sustainability was intended to rely on comparing Environmental Cost Indicators (ECI). However, this proved challenging due to the lack of a comprehensive Life Cycle Assessment (LCA) that includes all types of binders and aggregates. Therefore, conclusions are drawn based on factors such as energy usage, carbon dioxide emissions, and the incorporation of waste products in the concrete mix, in line with the eight actions proposed by de Oliveira Neto et al. [50], as introduced in Chapter 1. Additionally, cost evaluation is considered when cost is a limiting factor.

The final evaluation from the multi-criteria analysis considers all the properties studied according to the three design criteria—sustainability, bioreceptivity, and structural integrity, including compressive strength and FT resistance—along with the knowledge gaps identified in promising sustainable binders or aggregates that may enhance bioreceptive performance. While mechanical properties are taken into account, certain limitations are expected due to high porosity and aggregate gradation, which are known to reduce compressive strength [65] and, consequently, FT resistance [79].

3.2. Multi-criteria analysis for binder selection

In this section, the multi-criteria analysis for selecting the binder is presented, beginning with a brief introduction to the binder types used in the analysis, followed by the analysis and the conclusion on the binder.

3.2.1. Introduction

Ordinary Portland Cement (OPC)

OPC has long been used in civil infrastructure construction, making it the most popular, most used and cost-effective building material [80]. However, OPC binder is a high carbon emission binder product that requires high heating temperatures for clinker production. It is reported that the production of OPC accounts for approximately 5-8% of global carbon emissions annually [81]. This results in the annual production of no less than 2.1 billion tons of CO_2, with almost half of these emissions originating from the calcination process of limestone [82].

OPC with Supplementary Cementitious materials (SCMs)

Given the high environmental impact derived by OPC use in the concrete products, Supplementary Cementitious materials (SCMs), are used to reduce the consumption of OPC. SCMs mostly used are Ground Blast Furnace Slag (GBFS), Fly ash (FA) and Silica Fume (SF), all industrial by-products. GBFS is a by-product of the steel industry and can replace clinker in higher amounts reaching 80-95% replacement (CEM III/C) based on EN 197-1:2000 [83]. FA, is a by-product of coal-fired power plants and the replacement ratio ranges between 10 to 30%, as higher rates impact negatively the mechanical properties of the final concrete product due to its low reactivity [84]. Finally, SF is a by-product of silicon or ferrosilicon alloy manufacturing and has lower replacement rates ranging between 5 to 15%, as higher replacement rates are proven detrimental for compressive strength [84]. Replacement rates of SCMs are linked with the k-value as defined by the EN 206 standard. Specifically, the k-value is based on comparing the durability performance (or strength) of a reference concrete with cement ”A” to a test concrete where part of cement ”A” is replaced by an SCM. This comparison takes into account the water/cement ratio and the addition content [83]. For each different SCM, permitted k-values are specified, and different EU standards apply to each by-product used.

The amount of slag available worldwide is around 5-10% of the cement produced [85]. This amount is not likely to increase as the demand for steel is currently lower than the demand for concrete. At the same time, due to environmental pressures, more steel is being recycled, and steel scrap is increasingly used in the industry. Additionally, hydrogen ironmaking is gaining ground as a way to reduce CO_2 emissions compared to the current standard blast-furnace route [86]. Moreover, GBFS is only accessible in countries with a steel industry, which means longer transport distances are needed, leading to an increased environmental impact of the concrete product. Overall, the slag market is currently 100% saturated with uncertainties regarding future production due to the introduction of hydrogen-powered furnaces. On the other hand, FA is gradually diminishing in importance due to the ongoing decommissioning of coal and lignite power plants even if the amount of FA is higher reaching 30% compared to cement [85]. Consequently, the supply of FA will be significantly reduced in the near future [87]. Given the decreased supply of GBFS and FA, new SCMs are investigated for substituting the clinker in the concrete product. In Figure 3.1, the availability of common SCMs is presented, making clear the decreased availability of GBFS and FA.

Calcined Clays

Clays have gained significant attention due to their abundance and widespread availability [88] (Figure 3.1). Clays with up to 60% kaolinite content have shown the highest pozzolanic activity and are considered suitable for SCMs [88]. Pozzolanic activity involves the reaction between pozzolans and calcium hydroxide ($Ca(OH)_2$), a byproduct of cement hydration. This reaction produces additional calcium silicate hydrate (C-S-H), which enhances the strength and durability of concrete [89]. The presence of pozzolans helps improve the overall properties of concrete by contributing to the formation of beneficial binding compounds [89]. It has been demonstrated that even low-grade clays with at least 40% kaolin content can be used as SCMs, potentially providing high reactivity pozzolanic materials [90], [87]. The production of calcined clays requires equipment similar to that of OPC and involves a comparable investment cost. Additionally, the calcination process for clays, at temperatures between

750–850°C, consumes less energy compared to the clinker production process at 1450°C [91].

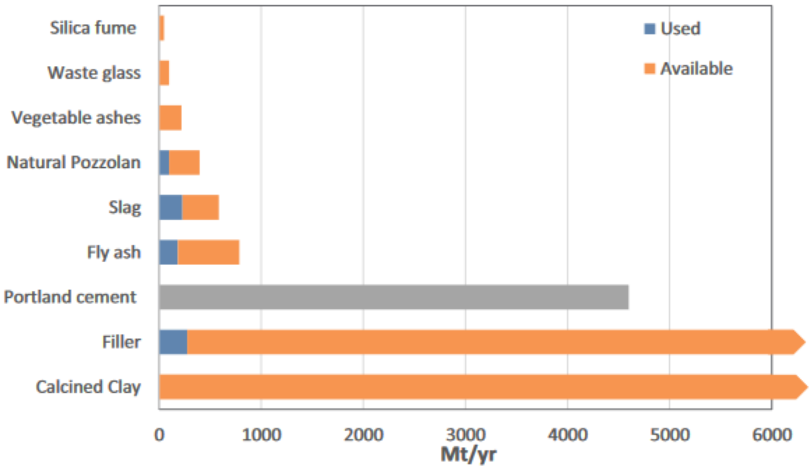


Figure 3.1: Availability of common SCMs [85].

Calcium Aluminate Cement (CAC)

CAC is hydraulic binder cement with monocalcium aluminate [92] as the main clinker and its main characteristic is the high-early strength development compared with OPC and is used mostly in applications involving extreme environments named refractories, acid-resistant requirements and fast-setting cement [93]. The required temperature for the formation of CAC is affected by the mineral phase and chemical composition of the constituent minerals of CAC and typically is in the range of 1400°C to 1600°C, showcasing an increase in the production temperature compared with OPC [93].

Calcium Sulfoaluminate Cement (CSAC)

CSAC is an alternative binder that gained attention due to its lower CO_2 emissions compared with OPC [94]. Limestone, bauxite and gypsum are the raw materials for the production of the CSA cement that are burned at temperatures ranging from 1250 to 1350 °C, resulting in a sulfate-based clinker [81]. Interesting characteristics of CSA include rapid strength development, anti-corrosion properties, particularly in resisting sulfate attack, and anti-freezing and thawing properties, making it very valuable in low-temperature concrete construction compared to OPC [80].

Magnesium Phosphate Cement (MPC)

MPC is a type of inorganic cementitious material that uses phosphate as a bonding phase. It is created by combining dead-burned magnesium oxide (an alkali component), soluble phosphate (an acid component), and additives in specific proportions through an acid-base chemical reaction under acidic conditions [95]. Compared to Portland cement, MPC offers advantages such as rapid hardening, high early strength, adaptability to ambient temperatures, minimal volume deformation, performance equivalent to Portland cement-based materials, wear resistance, frost resistance, and reinforcement protection [95].

However, the raw materials for MPC production are costly, particularly the high-cost dead-burned magnesia. Additionally, the calcination temperature is similar to clinker production (1600°C). Finally, the hardening speed of MPC is too fast, making the product difficult to control [96]. This means that there is limited time for placing and finishing the concrete product before it sets. Furthermore, due to the rapid hydration process of fast-hardening cement such as MPC, coupled with the elevated heat released, it is possible for early shrinkage cracking or thermal cracking to occur. Methods to delay the fast hardening of MPC include using retarders, lowering the Magnesium Phosphate ratio, or applying the concrete product in a negative temperature environment [96]. All these methods slow down the rate of hydration and increase the setting time, providing more time for placing and finishing.

Geopolymer

Geopolymer is formed by aluminosilicate materials with alkaline activators. Aluminosilicate materials can be divided into two groups based on the calcium content: low calcium and high calcium. Low calcium precursors include Class F FA, metakaolin (MK), SF, Rice Husk Ash (RHA), and Red Mud (RM), while high calcium precursors include GBFS and class C FA. Alkaline activator solutions such as sodium hydroxide, potassium hydroxide, sodium silicate, and potassium silicate are generally used to activate aluminosilicate materials [97]. The material's high compressive strength, durability, and resistance to environmental degradation make it suitable for various applications [97].

However, there are challenges related to material availability, as it relies on industrial by-products that can vary in composition and availability in different regions, alkaline activator handling, and standardization [97]. In addition to that, geopolymers are considered advantageous materials for the concrete industry when innovative binders are employed, rather than relying solely on commonly used materials like slag. However, due to the saturated market for slag, achieving a lower CO_2 footprint with geopolymer may not be guaranteed on a global scale.

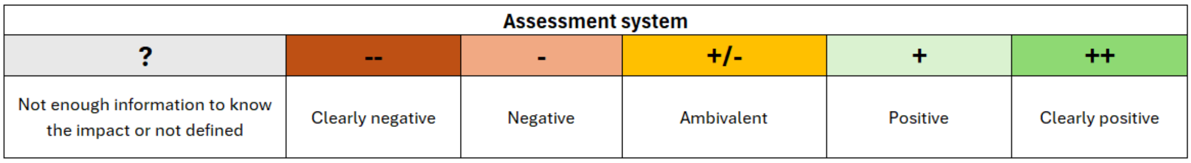
3.2.2. Analysis

In order to opt for the binder to use in the concrete product, a multi-criteria analysis is performed. The criteria chosen for the selection as already presented in Section 3.1 are:

- The use of the binder in a porous concrete product for verification of plant growth either in the building envelope or vegetation porous concrete.
- The cost of the binder as a limiting factor.
- The environmental performance of each binder in terms of CO_2 emissions and allocation. Life cycle assessment (LCA) was intended to be used as the primary environmental management technique to assess the impacts of the binder products. However, due to varying goals and scopes, fluctuating inventory allocation, uncertain data quality, specific geographic locations, and various mix designs, focus was given to CO_2 emissions as the main environmental category affected by the binder. Additionally, economic allocation's impact was considered when SCMs are taken into account.
- The influence of the binder on the mechanical properties of a concrete product, such as compressive strength and freeze-thaw resistance. It is important to highlight that factors like compressive strength and freeze-thaw resistance are influenced not only by the binder used but also by the high porosity of the porous concrete product. The assessment of compressive strength is based on findings from porous concrete products found in the literature (Chapter 2), whereas freeze-thaw resistance, being a property not studied for the different binder for porous concrete, is evaluated based on traditional concrete products.
- The bioreceptivity performance of each binder in terms of alkalinity and plant growth.
- Availability of materials.

Assessment system

The comparisons between the binder types are mostly compared with OPC, as it is identified the most used binder in the civil engineering infrastructure. In the analysis, a positive or negative impact assessment is used, as shown in Figure 3.2, rather than a grading and weighting system.



Assessment system					
?	--	-	+/-	+	++
Not enough information to know the impact or not defined	Clearly negative	Negative	Ambivalent	Positive	Clearly positive

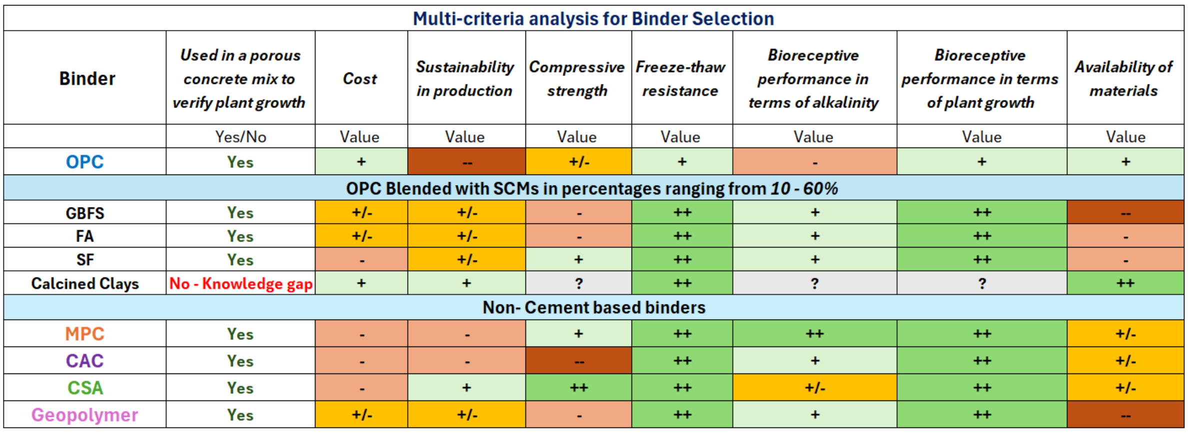
Figure 3.2: Assessment system used for Multi-criteria analysis of binder.

This decision is based on the absence of numerical outputs for every criterion studied, making formative and grading comparisons less relevant for the multi-criteria analysis. For example, plant growth lacks specific values for comparison due to the different methods of germination calculation. Cost prices are variable and depend on market values in different regions and continents. Additionally, the lack of studies on freeze-thaw resistance in porous concrete structures is an important gap, and the reliance on traditional concrete data also limits the ability to perform and use numerical analysis. Finally, sustainability comparisons could not be clearly made based on the LCA assessment but rather on specific environmental indicators widely used in the literature, particularly CO_2 emissions, identified as the main pollution source in binder production. Economic allocation was considered to evaluate its impact on the environmental performance of the concrete product, especially when using by-products as SCMs.

Taking everything into account, a positive and negative system is judged to be the most relevant, given the literature findings, to establish a unified grading system for all criteria. Otherwise, a separate grading system for each category would be necessary, which would not allow for a comprehensive multi-criteria analysis of the different properties studied.

Evaluation

The evaluation of different binders is illustrated in Figure 3.3 according to the assessment system. The conclusions derived from Figure 3.3 are stated below.



Multi-criteria analysis for Binder Selection								
Binder	***Used in a porous concrete mix to verify plant growth***	***Cost***	***Sustainability in production***	***Compressive strength***	***Freeze-thaw resistance***	***Bioreceptive performance in terms of alkalinity***	***Bioreceptive performance in terms of plant growth***	***Availability of materials***
	Yes/No	Value	Value	Value	Value	Value	Value	Value
OPC	**Yes**	+	--	+/-	+	-	+	+
OPC Blended with SCMs in percentages ranging from *10 - 60%*								
GBFS	**Yes**	+/-	+/-	-	++	+	++	--
FA	**Yes**	+/-	+/-	-	++	+	++	-
SF	**Yes**	-	+/-	+	++	+	++	-
Calcined Clays	**No - Knowledge gap**	+	+	?	++	?	?	++
Non- Cement based binders								
MPC	**Yes**	-	-	+	++	++	++	+/-
CAC	**Yes**	-	-	--	++	+	++	+/-
CSA	**Yes**	-	+	++	++	+/-	++	+/-
Geopolymer	**Yes**	+/-	+/-	-	++	+	++	--

Figure 3.3: Binder assessment

Use in a porous concrete mix to verify plant growth

Considering the first criterion, it can be observed from Figure 3.3 that various binder types have been utilized in the literature to assess the bioreceptivity performance of concrete products. Most research has focused on OPC supplemented with SCMs, as presented in Tables 2.3 and 2.4 in Chapter 2. SCMs are used to reduce the alkalinity of OPC and the use of clinker, making concrete products more environmentally friendly. Furthermore, non-cementitious binders have been investigated as substitutes for traditional cement, as presented in Chapter 2. One type of binder that has not been studied for its bioreceptivity performance is Calcined Clay cement, indicating a gap in the current literature.

Cost

Regarding cost, OPC is identified as the lower-priced binder given its increased use compared with other binders. However, prices of OPC can vary significantly from country to country and are subject to regional fluctuations, which is why its assessment is positive but context-dependent. Among SCMs, SF is the most expensive by-product, resulting in a negative assessment compared to GBFS and FA [84]. The cost of these by-products is influenced by their market availability, demand, and transportation costs, leading to an ambivalent score. Regarding calcined clays, the cost of the materials is documented as close to the OPC materials, making their use economically feasible [85]. In regions where the cost of other SCMs is high or their quality does not allow sufficient clinker replacement, clays can serve as a viable alternative [90], resulting in an assessment comparable to OPC. Conversely, MPC is identified as a high-cost binder due to the expense of its main component, dead-burned magnesia, limiting its use [96]. CAC is four to five times more expensive than OPC due to its limited production scale and high raw material costs, particularly bauxite [98]. For CSA, the high cost of alumina-bearing raw materials, especially bauxite, also limits its use. Consequently, all alternative binders (MPC, CAC, CSA) are associated with high costs, resulting in a negative assessment. Finally, the cost of geopolymer cement is influenced by the prices of SCMs and alkali activators. Alkali activators, especially sodium silicate, represent the primary cost factor [99] [100]. Due to the variability in costs associated with both SCMs and activators, an ambivalent assessment is given.

Sustainability in production (focused on CO_2 emissions and economic allocation)

Comparing the sustainability performance of different binders using the Environmental Cost Indicator (ECI) is challenging due to the lack of comprehensive Life Cycle Assessments (LCAs) that include all binder types and consistent parameters [101]. Consequently, it is difficult to directly compare the ECI of each binder. While CO_2 emissions during binder production are well-documented and serve as the primary comparison metric, the overall sustainability performance should ideally be evaluated using a full range of environmental impact indicators, not just carbon emissions. However, limitations in the existing literature restrict such comprehensive assessments.

Starting with OPC, it has been reported as the most CO_2-intensive material during concrete production, with emissions ranging between 0.73–0.85 tons per ton of OPC [102]. In contrast, the production of 1 ton of CSA can reduce CO_2 emissions by 0.25 - 0.35 tons, depending on the composition [103], [104]. CAC production generates 15% less emissions than OPC, approximately reducing CO_2 by 0.12 tons per ton of binder [92]. While MPC is bioreceptive [42], its calcination temperature reaches as high as 1600°C [33], and, based on available literature, lower CO_2 emissions are not documented.

Regarding documented by-products such as GBFS, FA, and SF, and geopolymers associated with these by-products, a more comprehensive approach is taken when researching their environmental impact on carbon emissions. According to the Waste Framework Directive [105], these products are not considered waste but by-products. Consequently, their production impact must be considered, and an allocation method is used. The Dutch Handbook on LCA advises economic allocation as the baseline method if allocation is required [106]. This means the environmental impact is divided according to the economic value of the co-products, making the final environmental impact of a concrete product variable due to market volatility and price fluctuations [107], [108]. Thus, even if OPC with SCMs is considered a lower-carbon concrete product, its impact can vary due to economic monopolies, higher demand, and lower supply, which can cause environmental impact fluctuations [109].

Apart from economic allocation, the decrease in CO_2 emissions is connected with the substitution rates of the SCMs. It is reported that for GBFS, emissions reductions can be from 0.3 to 0.7 tons of CO_2 per ton of binder when substitution is in the range of 30 to 70% [110]. The mitigation potential of alkali-activated materials (geopolymers) based on GBFS and FA can reduce emissions by 40 to 80% compared to OPC [109], a decrease of 0.32 - 0.63 tons of CO_2 per ton of binder. Finally, regarding OPC with calcined clays—calcined clay cement—is also a low-carbon alternative as clinker substitution can be up to 50% [90]. The calcination process for clays occurs at temperatures between 750–850°C, significantly lower than the clinker production temperature (1450°C). It has been reported that the use of calcined clays can decrease CO_2 emissions by 30 - 40%, a reduction of 0.24 - 0.32 tons of CO_2 per ton of binder [90]. Table 3.1 below, presents the CO_2 emissions as reported in the literature for the different binder types presented.

Table 3.1: CO_2 emissions per binder type.

Binder Type	**tCO_2 emissions/t of binder**	**Source**
OPC	0.73-0.85	[102]
CSA	Reduction: 0.25-0.35t	[103], [104]
CAC	Reduction: 0.15t	[92]
GBFS	Reduction: 0.3-0.7t Substitution: 30-70% Economic allocation related	[110]
Geopolymers (based on GBFS & FA)	Reduction: 0.34-0.68t Economic allocation related	[109]
C^3	Reduction: 0.26-0.35t Subtitution: up to 50%	[90]
All reductions in CO_2 emissions presented are based on the average emissions reported for OPC.		

The assessment takes into account reported carbon emissions (see Table 3.1) and the impact of economic allocation in the production of SCMs and geopolymer concrete products. OPC is evaluated with a clearly negative impact due to its high reported emissions and widespread use in concrete products. OPC combined with SCMs is rated as ambivalent because, while this combination can reduce CO_2 emissions significantly, the final environmental impact varies based on economic allocation, as well as the influence of economic monopolies and demand. The same ambivalent assessment applies to geopolymer products. MPC and CAC receive a negative assessment because they do not significantly reduce CO_2 emissions and are not as widely used as OPC. CSA is assessed positively due to its reported reduction in CO_2 emissions, which are a major contributing factor to the environmental impact when assessing binders. Finally, calcined clays are found to decrease emissions, resulting in a positive assessment.

Mechanical properties

- **Compressive strength:** Regarding compressive strength, the assessment is based on porous concrete mix designs as identified in the literature review in Chapter 2. The compressive strength property in the concrete mix is influenced by various factors beyond binder selection, such as porosity and aggregate gradation, size and type. However, comparisons between different binders have revealed some notable outcomes from a general viewpoint.

  Regarding OPC, an ambivalent assessment is given due to fluctuating strength outcomes based on porosity, aggregate gradation, and size, with strength values ranging from 2 to 10 MPa [38, 41, 6]. When SCMs were incorporated in the concrete product to substitute OPC in variant substitution rates, compressive strength was negatively affected in percentages greater than 40% for GBFS [76] and up to 30% for FA [111, 77]. That is why a negative assessment is given compared with the ambivalent assessment of the OPC. On the other hand, the use of SF showed an increase in the compressive strength property [37] and a positive assessment was given. CAC shows the lowest compressive strength in porous concrete mix designs, with values ranging from 1 to 2 MPa [75]. It receives a clearly negative assessment as it has the lowest compressive strength reported in the literature among all the binders studied. MPC was found to increase compressive strength compared with average OPC compressive strength values (reaching up to 7 MPa), with further enhancement observed by incorporating BFS [42] and receiving positive assessment. Finally, CSA has been proven to lead to improved compressive strength, achieving up to 90 MPa when using coarse aggregates with particle sizes ranging from 19.0 to 26.5 mm and limestone powder [78]. This is why a clearly positive assessment is given. However, its application in porous concrete is limited [78]. Regarding the C^3 binder, its use in bioreceptive porous concrete has not yet been studied in the literature. Therefore, insufficient information was found to assess this property. However, it has been found that the main advantage of C^3 is its ability to be produced with clinker factors as low as 40% to 50% without a reduction in mechanical performance after a few days [90, 112]. This can be promising, although this observation is for conventional concrete and not porous concrete, which tends to negatively impact the compressive strength property.

- **Freeze-thaw resistance:** Freeze-thaw resistance of bioreceptive porous concrete products has not been established. However, binder selection affects this property and has been studied in the literature for conventional concrete products, with comparisons made to OPC. All SCMs have been found to increase the freeze-thaw durability of concrete compared to OPC, which is why a clearly positive assessment is given compared with the positive assessment given to OPC. Specifically, FA can reduce the ingress of external water into concrete due to the filling effect of the micro-FA particles [113, 114]. Additionally, several studies have shown improvements in freeze-thaw durability in SF-OPC blended cements [113, 114]. Metakaolin, a calcined clay with a high amount of kaolin, has also been found to increase freeze-thaw durability, reducing weight loss more effectively than OPC control products. This improvement is due to metakaolin refining the internal pores of concrete, reducing porosity and water absorption, thus lowering freeze-thaw damage [113]. Similarly, the addition of GBFS has also resulted in reduced freeze-thaw durability damage to concrete products [113]. MPC has been found to improve the water freeze-thaw resistance of concrete mortar specimens compared to OPC mortar specimens [95]. Geopolymers have a positive impact on freeze-thaw resistance compared to OPC concrete, as indicated by measures such as compressive strength and mass loss [115, 116]. CSA has also been shown to perform better in freeze-thaw resistance than OPC, as measured by the relative dynamic modulus, weight loss, and surface scaling [80, 117]. Limited laboratory data exists on the freeze-thaw resistance of CAC. However, studies indicate that CAC concretes exhibit good freeze-thaw resistance when porosity is low [118].

  It should be noted, however, that binder evaluation on freeze-thaw resistance is based on conventional concrete products. In porous concrete, freeze-thaw resistance is primarily affected by coarse aggregate size, distribution (PSD) and porosity [79]. Electron microscopy has shown that freeze-thaw deterioration of porous concrete mainly occurs in the interfacial transition zone, the area between the coarse aggregate particles and the cement paste matrix [119]. Therefore, any positive effects observed in freeze-thaw durability do not necessarily apply to porous concrete products and may, in fact, lead to a lower durability factor compared to conclusions drawn for traditional concrete. This is because larger aggregate sizes increase interconnected pore availability for water absorption, coupled with the weakened bonding force between the cement matrix and coarse aggregates. Both factors ultimately reduce the freeze-thaw resistance of the porous product [79].

Bioreceptivity performance in terms of alkalinity
MPC shows the highest decrease in alkalinity, with pH values ranging from 7.5 at 0 days to 7.7 at 28 days of curing, resulting in a clearly positive assessment. However, the incorporation of GBFS increases the MPC's pH to 8.5 at 28 days [42]. MPC's pH results from 0 to 28 days indicate an initial increase in pH within the first 5 days, followed by stabilization or a slight further increase by 28 days. OPC has the highest alkalinity, with pH values ranging from 12 to 13. Natural carbonation quickly reduces OPC's surface pH, reaching almost 9 [6]. Therefore, OPC receives a negative assessment rather than a clearly negative one. When SCMs are incorporated into the OPC mix [40] or when the SCM content is increased [120], the pH value decreases, leading to a positive assessment for all SCMs in this criterion. An interesting observation is that increasing the alkali activator content results in a higher pH after 28 days of curing [74]. However, at lower alkali activator percentages, the pH remains lower than that of OPC, which is why a positive assessment is given [40]. CSA shows contradictory results regarding alkalinity. Gong et al. [78] found pH values slightly above or below 10 (ranging from 9.6 to 10.4) after 28 days, depending on the limestone powder content, while Cao et al. [111] reported a pH of less than 8.5. This results in an assessment that is neither clearly positive nor negative. Finally, CAC is reported to have lower alkalinity compared to OPC [121], though specific pH reductions are not well-documented. Despite this, CAC is given a positive assessment.

In addition to all the aforementioned findings, pH for all different binders studied decreases as the curing period increases, showing higher pH results after 1 and 3 days and lower results after 28 days of curing. This behavior is observed uniformly except for the MPC binder, where an increase in pH is noted after 5 days/curing, followed by a smaller decrease or stabilization of the pH until 28 days/curing.

Bioreceptivity performance in terms of plant growth
Assessing bioreceptive performance in terms of plant growth proved challenging due to the wide variability in binder types, aggregate sizes and types, admixtures, and growing substrates used in the studies. Additionally, the methods for testing bioreceptivity varied from research to research, including measures such as plant height, diameter, and fresh or dry biomass of the plants. As a result of these variations, quantifying and assessing plant growth among different binders is difficult. Consequently, the same clearly positive assessment score is given to all binders when germination is proven successful. However, OPC received a positive assessment as it is used as the reference mix in most studies compared to other mixes and showed later germination and performed worse in germination rates. Finally, C^3 has not been investigated for its impact on plant growth. Given its potential as a substitute for OPC in the coming years, evaluating its bioreceptivity performance is a crucial gap that should be addressed.

Availability of materials
This criterion identifies the material availability for producing each different binder. As already discussed, SCMs are expected to be in low supply in the coming years due to increased scrap use in the iron industry and the decommissioning of coal plants, which impacts the availability of GBFS and FA respectively. The availability of common SCMs is depicted in Figure 3.1, highlighting the need for substitutes for GBFS, FA, and SF. A clearly negative assessment is given to GBFS, given its low availability and higher substitution rate of OPC compared with the other SCMs that assessed with a negative grading. On the other hand, clay deposits are abundant and can replace a significant amount of clinker in concrete products (clearly positive assessment). The high cost of MPC, CAC, and CSA limits their use and global acceptance as substitutes for OPC, despite being available, as a result an ambivalent assessment is given.

3.2.3. Final selection of binder

Based on the binder assessment presented in Figure 3.3, Calcined Clay Cement (C^3) is identified as the most promising binder for evaluating bioreceptivity performance, considering its wide availability and the declining availability of other SCMs due to market changes and environmental guidelines in the construction sector. C^3 is also recognized as the future low-carbon alternative for binder products for engineering construction by the United Nations and is already in use across Latin America [122]. Regarding the assessment of mechanical properties, data on the compressive strength of porous concrete with C^3 binder could not be found to the best of the author's knowledge. However, for conventional concrete, no reduction in compressive strength performance was observed after a few days [90], and freeze-thaw (FT) resistance was found to increase compared to conventional OPC products [113]. Nonetheless, conclusions for porous concrete remain unclear, and it is estimated that the mechanical properties may decrease due to high porosity. This creates an additional knowledge gap that should be addressed if C^3 binder is expected to replace OPC in the coming years.

At the same time, it should be taken into account that the viability of any technology is dependent on four important factors:

1. Technical viability
2. Economic feasibility
3. Low capital investment
4. Easy availability of raw materials

C^3 fulfills all these criteria since its calcination process can use a normal rotary kiln, as is already used for OPC. Global C^3 production capacity is expected to reach 90 million tonnes annually by 2025, and the availability of clays is significant, posing no additional economic problems. Additionally, the similarity of C^3 cement to other cements containing SCMs means there should be no major barriers to acceptance [85]. Finally, preliminary studies indicate that the cost of C^3 production can be lower than that of currently produced alternatives (significantly lower than plain Portland materials and potentially lower than other SCM blends, depending on the local availability and price of these materials) [85].

MPC, CAC, and CSA are not chosen primarily because their materials are costly, limiting its use for becoming wide available in the market. Additionally, MPC and CAC do not perform much better in terms of CO_2 emissions due to their high calcination temperature, which is close to or even higher than that of OPC. Even if CSA has demonstrated positive outcomes in terms of mechanical properties, and its bioreceptivity performance has already been studied, its high material cost remains a constraint for widespread application in the concrete industry. This is evident from the limited number of publications not discussing its potential replacement of OPC in the near future.

As a result, it is a priority to investigate the bioreceptivity performance of C^3, a lower-carbon binder, given its anticipated use in various countries within and outside the EU in the years to come.

3.3. Multi-criteria analysis for aggregate selection

In this section, the multi-criteria analysis for selecting the aggregate type is presented, initiating with a brief introduction to the different aggregate types used in the analysis, followed by the analysis and the conclusion on the aggregate type.

3.3.1. Introduction

Natural aggregates

- **Crushed stone - Limestone**: Limestone aggregate is a commonly used irregular and angular natural aggregate in civil infrastructure. Its benefits include good strength, low risk of alkali-silica reaction, and reduced drying shrinkage in concrete [123]. However, it is not typically used in the Netherlands as it is not locally available and should be imported from Belgium and/or Germany [124]. The production process of limestone is energy intensive and requires land use due to quarrying, resulting in noise and air pollution.
- **Crushed gravel - River gravel**: River gravel is a smooth, cubic-shaped aggregate commonly found in riverbeds, streams, and floodplains. In the Netherlands, river gravel is more readily available than limestone, making its use more frequent [124]. The gravel aggregate its mechanically dredged in the Netherlands posing some environmental issues as habitat disruption, water quality issues, and erosion in the natural environment [124].

Lightweight aggregates

- **Crushed Expanded Clay (CEC)**: CEC are made by clay mixed with or without lime in a rotary kiln with a temperature ranging between 1.110 to 1.300 °C. The clay expands five to six times its original size and takes the shape of a dark or reddish-brown pellet with different sizes ranging from 0.1 to 25 mm. CEC is mostly used in lightweight structures.
- **Lava stone**: Lava stone aggregates are lightweight aggregates that occur naturally and are formed from volcanic activity. As the lava cools, it forms a porous and well-sintered mass. Once the magma has cooled sufficiently, an amorphous and porous structure is produced. These materials are commonly known as volcanic aggregates. Before use, are mechanically crushed and sieved to ensure consistent quality [125].

Recycled aggregates

- **Recycled Concrete Aggregate (RCA):** Recycled concrete aggregates are a waste stream of the building sector, produced after crushing waste building materials into small particles and removing contaminants such as metal, plastic, and wood. Construction and Demolition Waste (CDW) is a significant waste stream in Europe. The amount of CDW is expected to increase over time, with many concrete structures built after World War II now reaching the end of their life [126], [127]. In the Netherlands, about 25 million tonnes of CDW are generated annually, accounting for 46% of the country's total waste [126]. The EU Waste Directive aims for a minimum of 70% re-use, recycling, and material recovery of non-hazardous CDW by 2020 [128]. The Netherlands already exceeds this target with a recycling rate of 95% [126], [129]. However, the use of CDW is primarily seen in road applications, where it undergoes down-cycling instead of being reintroduced into the building sector as clean aggregate. This fails to meet the circular economy requirement of reusing this byproduct in the same sector and reducing the need for natural aggregates [130].
- **Recycled Brick Aggregate (RBA)**: RBA is a waste stream that comes from the demolition sites of building structures. First, other waste streams are removed by sorting process technologies, and then the aggregate is crushed and screened to produce different aggregate fractions. Brick waste (BW) is the second most generated type of CDW, after concrete waste [131].
- **Reclaimed Asphalt Pavement (RAP)**: Recycled or reclaimed asphalt pavement (RAP) is a readily available construction waste stream obtained from milling and removing old asphalt pavement in preparation for replacement. RAP has been widely utilized to supplement virgin mineral aggregates and bitumen in hot mix asphalt [132]. However, its use is being studied for replacement of natural aggregates in the concrete product.
- **Blast Furnace Slag (BFS)**: BFS is generated as a by-product of pig iron in blast furnaces. It is poured into beds and slowly cooled under ambient conditions, forming a crystalline structure that can subsequently be crushed and screened producing different aggregate fractions [133].
- **Steel Slag Aggregate (SSA)**: SSA is also a by-product of the steel industry and is generated through the separation process of molten steel and impurities in steel-making furnaces. SS can be reused as an aggregate and a cementitious material. The difference between BFS and SSA is the iron oxide concentration, which in the case of SSA is almost 16 - 25% compared to BFS which is roughly 0.7% [134].

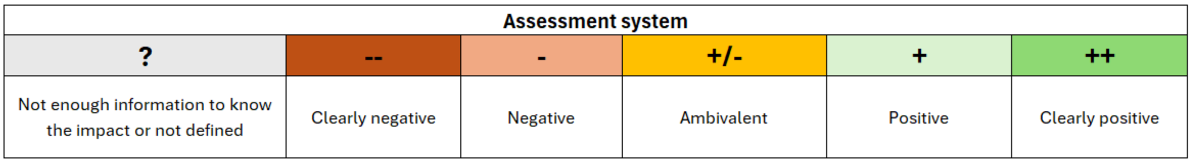
3.3.2. Analysis

In order to opt for the aggregate type to use in the concrete product, a multi-criteria analysis is performed. The criteria chosen for the selection as already presented in Section 3.1 are:

- The use of each aggregate type in a porous concrete product for verification of plant growth either in the building envelope or vegetation porous concrete.
- The sustainability in the production process and economic allocation. When assessing the sustainability of aggregates, it is challenging to compare them based on LCAs due to the lack of comprehensive LCAs that include consistent assessment criteria for all aggregate types. In addition, the impact of aggregates is considered as part of the material extraction for the concrete product, but the primary focus remains on the environmental impact assessment of the binder. This emphasis limits the opportunity to compare different types of aggregates, as the binder has a more significant influence on the final environmental performance of the concrete product. Consequently, assessing the sustainability performance of aggregates is challenging. The focus is on the production processes, including oil and energy consumption, as well as the economic allocation impact when applicable.
- The influence of the aggregate type on the mechanical properties of a concrete product, such as compressive strength and freeze-thaw resistance. In terms of mechanical properties, FT resistance has not been extensively analyzed for porous concrete products. However, conclusions can be drawn based on traditional concrete products.
- The bioreceptivity performance of each aggregate type in terms of porosity and water absorption.
- The bioreceptivity performance in terms of plant growth. It is important to note that while most recycled aggregates are not tested for their bioreceptivity performance, a grade is assigned after considering bioreceptive properties such as water absorption and porosity.
- Availability of materials.

Assessment system

The comparisons between the aggregates are mostly compared with the natural aggregates, as the most used types of aggregates in the civil engineering infrastructure. For the analysis, a positive or negative impact assessment is used, as presented in Figure 3.4 below.



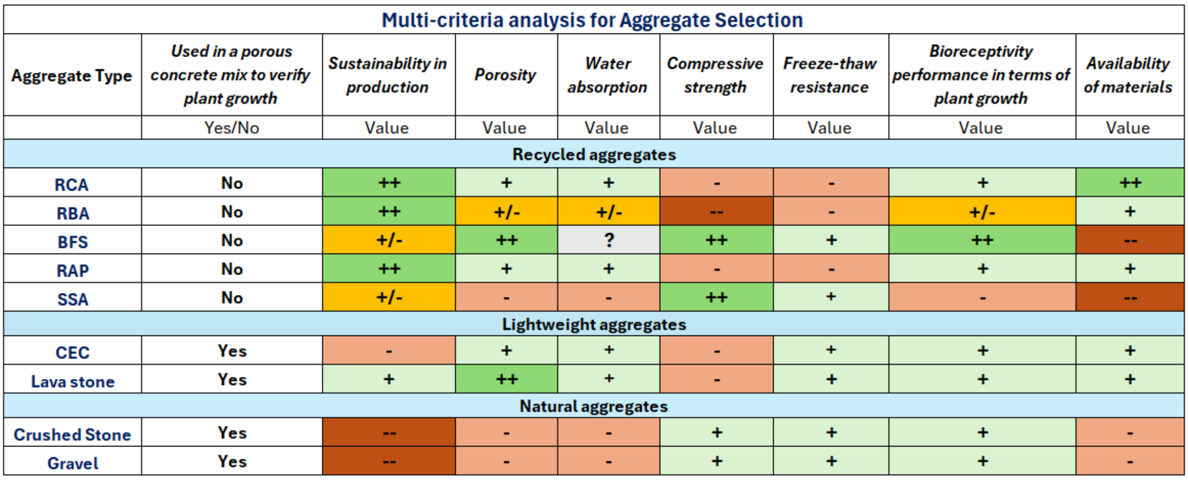
Assessment system					
?	--	-	+/-	+	++
Not enough information to know the impact or not defined	Clearly negative	Negative	Ambivalent	Positive	Clearly positive

Figure 3.4: Assessment system used for Multi-criteria analysis of aggregates.

In the context of decision-making for the grading system, the same rationale applied to the binder is also relevant to aggregate assessment. This is because without numerical outputs for every criterion studied, comparing formative and grading assessments becomes less meaningful for multi-criteria analysis. A more comprehensive explanation for the use of the chosen assessment system can be found in Section 3.2.2.

Evaluation

The evaluation of different aggregates is presented in Figure 3.5 according to the assessment system. The conclusions derived from Figure 3.5 are stated below.



Multi-criteria analysis for Aggregate Selection

Aggregate Type	*Used in a porous concrete mix to verify plant growth*	*Sustainability in production*	*Porosity*	*Water absorption*	*Compressive strength*	*Freeze-thaw resistance*	*Bioreceptivity performance in terms of plant growth*	*Availability of materials*
	Yes/No	Value	Value	Value	Value	Value	Value	Value
Recycled aggregates								
RCA	No	++	+	+	-	-	+	++
RBA	No	++	+/-	+/-	--	-	+/-	+
BFS	No	+/-	++	?	++	+	++	--
RAP	No	++	+	+	-	-	+	+
SSA	No	+/-	-	-	++	+	-	--
Lightweight aggregates								
CEC	Yes	-	+	+	-	+	+	+
Lava stone	Yes	+	++	+	-	+	+	+
Natural aggregates								
Crushed Stone	Yes	--	-	-	+	+	+	-
Gravel	Yes	--	-	-	+	+	+	-

Figure 3.5: Aggregate type assessment

Used in a porous concrete mix to verify plant growth

In literature, various types of aggregates are used for porous concrete, as discussed in Chapter 2. The most commonly used aggregate is natural, particularly crushed limestone. Additionally, alternative types such as crushed expanded clay and lava stone have been studied for their improved water absorption capacity. However, limited research has been focused on integrating waste products into mix designs for bioreceptive porous concrete.

Sustainability in production (focused on oil & energy consumption, and economic allocation)

The sustainability of aggregates is assessed based on their impact on the natural environment and the processes involving oil and energy consumption. To the best of the author's knowledge, a comprehensive Life Cycle Assessment (LCA) is not available in the literature. Additionally, the impact of aggregates on LCAs is evaluated as part of various concrete products, with the primary focus not on the environmental impact of aggregates themselves, but rather on the raw material extraction of the concrete product, where the binder has the most significant influence.

Natural crushed stone aggregates, obtained from quarrying and crushing bedrock, involve a huge requirement for energy and water, in addition to CO_2 emissions [135]. Gravel extraction involves the use of oil-consuming dredging vessels, leading to environmental issues like water pollution and erosion. Both crushed stone and gravel aggregates are negatively evaluated due to the energy and oil consumption required for their acquisition (clearly negative). On the other hand, recycled aggregates, such as RCA, RBA, and RAP, are considered the most sustainable option (clearly positive) as they are waste products from other processes and can be reused, effectively giving them a second life. According to the Waste Framework Directive [105], waste products are considered zero-burden when used as half-products for a new life cycle. The environmental burdens associated with their treatment prior to reintroduction into a new life cycle are accounted for in the LCA from the disposal of the original building or pavement structures. When considering by-products (BFS and SSA), economic allocation can impact the final environmental assessment due to market volatility and price fluctuations [106] and an ambivalent assessment is given. Lightweight aggregates are generally considered more environmentally friendly than natural aggregates. Lava stones are positively assessed compared to CEC because they are naturally occurring and require only mechanical processes such as crushing and sieving before use. In contrast, CEC requires the use of heat in a rotary kiln at high temperatures, leading to energy consumption and CO_2 emissions [125], hence the negative assessment.

Porosity & Water absorption: In terms of bioreceptivity performance, two properties of the aggregates are important: porosity and water absorption, with each one correlating with the other.

- **Porosity:** Focusing on porosity, most of the aggregates assessed have higher porosity than natural aggregates. Especially, lightweight aggregates are high-porous aggregates that increase the porosity of the final concrete product [136], [137]. Same conclusions are found for most of the recycled aggregates, with the BFS showing the highest porosity results compared with natural aggregates (clearly positive) [72], followed by RCA (positive assessment) [138, 139, 140, 141, 142, 143] and RAP (positive assessment) [132]. On the other hand, RBA had ambivalent outcomes with articles presenting increased porosity compared with NA [144] and other decreased [145]. This can be attributed to the different types of clay brick aggregates being studied and the quality of the final reclaimed product. A negative performance in porosity is found for SSA [146].
- **Water absorption:** Regarding water absorption, most of the aggregates that showed increased porosity also demonstrated high water absorption performance, which influenced the grading presented in Figure 3.5.

Mechanical properties

- **Compressive strength:** Recycled aggregates showed a trend of decreasing compressive strength of the final concrete product, with the highest negative impact found for RBA [145]. This is why RBA receives a clearly negative assessment compared to RCA and RAP which both receive a negative assessment. All three are evaluated compared to natural aggregates. On the other hand, both BFS [71, 72] and SSA [146], [147] showed a positive effect on the compressive strength compared with natural aggregates, assessed with a higher positive assessment (clearly positive). Finally, regarding lightweight aggregates, it has also been reported that they have a negative impact on the compressive strength of the final concrete product [148] and a negative assessment is given.
- **Freeze-thaw resistance:** In terms of mechanical properties, freeze-thaw (FT) resistance has not been extensively analyzed for porous concrete products. However, conclusions can be drawn based on traditional concrete products. A trend is observed where a decrease in compressive strength correlates with a decrease in the FT durability factor.

  It is found that RCA and RAP result in lower FT resistance compared with normal aggregates (negative assessment). For RCA, the replacement rate plays an important role in the freeze-thaw performance of the concrete product, showing a declined tendency in FT resistance with the increase of recycled aggregates [149]. Regarding RAP, reduced FT durability is observed as the fraction of virgin coarse aggregate replaced with RAP increased from 50% to 100% (negative assessment) [150]. The same negative impact on FT is found when RBA substituted NA in higher proportions [151]. On the other hand, SSA and BFS showed better results in FT resistance (positive assessment) [71]. For SSA, a positive effect on FT resistance is reported due to the improvement in the Interfacial Transition Zone (ITZ) and microstructure of SS aggregate with the binder paste [148]. Finally, studies on both lightweight aggregates showed improved FT resistance compared with natural aggregates. However, it should be noted that the substitution rate was up to 30%, and only fine aggregates were tested [137], [152]. That is why a positive assessment is given as the evaluation of the FT resistance was made based on the fine aggregates and not on coarse aggregates used in porous concrete products.

It is important to note that FT resistance is not assessed for porous concrete products. It is expected that for porous concrete, FT resistance is affected by the high void ratio, increased pathways for water absorption and undergoes decrease.

Bioreceptivity performance in terms of plant growth
Bioreceptivity in terms of plant growth is influenced by both aforementioned properties—porosity and water absorption—although clear comparisons were difficult to identify in the literature. Firstly, to the best of the author's knowledge, most recycled aggregates have not been assessed for their bioreceptive performance in the literature. Moreover, there is no consistent method for evaluating plant growth, which makes assessment challenging. Consequently, all aggregate types deemed suitable for germination and plant growth were graded with the same score.

However, BFS aggregates are graded higher than other types of aggregates because their plant growth was compared with crushed aggregates and found to be superior in terms of plant height [71]. It should be noted that many recycled aggregates, including RCA and RAP, are expected to support plant growth due to their physical properties (porosity and water absorption). For RBA, although its porosity and water absorption were found to be lower compared to RCA [145], a study on crushed fire clay brick building material showed enhanced bioreceptivity performance for plant growth compared to ordinary concrete building material [5]. Thus, the impact of RBA aggregates is ambivalent and may vary based on the specific properties of recycled clay brick aggregates in contrast to fire clay brick building material.

Lastly, lightweight materials also received positive assessments based on their bioreceptive properties of porosity and water absorption and have already been used and performed positively for plant germination [31], [34], [38].

Availability of materials
This criterion identifies the aggregate availability to be used as concrete aggregates. RCA is recognized as the most important waste stream in building infrastructure, expected to increase in the coming years due to the reaching of End-of-Life (EoL) concrete structures as presented in Introduction 3.3.1. That is why a clearly positive assessment is given. RBA and RAP are also identified as significant waste streams from building structures and pavement infrastructure respectively (positive assessment) [131], [153]. BFS and SSA are facing availability issues as presented in Section 3.2.1 and in the availability of SCMs (Figure 3.1), resulting in a clearly negative assessment. Lightweight materials are judged to be better in terms of availability compared with NA due to their less use in concrete products (positive assessment). NA are not infinite and have been extensively used in civil engineering infrastructure for decades and a negative assessment is given.

3.3.3. Final selection of aggregates

Based on the aggregate type assessment presented in Figure 3.5, research gaps are identified for the use of recycled aggregates in the bioreceptivity performance of porous concrete. BFS shows a more positive impact on the different criteria tested (porosity, compressive strength, plant growth) compared with natural aggregates. However, their use is not preferred due to their decreased availability [85] and economic allocation used during their environmental assessment that can modify their environmental performance based on the economic monopolies. Following this, RCA and RAP have the potential to be used in porous concrete products. Given that RCA is the primary waste stream in the EU and the Netherlands, and with the intention to meet the circular economy needs, it is selected as the most appropriate RA to be tested in the porous concrete product. The decision is further explained, considering that over half of the raw materials (gravel, sand, and cement) used for concrete production depend on imports in the Netherlands [129]. Additionally, RCA exhibits good physical properties (increased porosity and water absorption compared with natural aggregates) that are promising for plant growth.

In addition to recycled concrete aggregates, lava stone is considered for testing on bioreceptive porous concrete due to its positive effects on porosity and water absorption. Germination has already been tested and proven possible, further justifying the inclusion of lava stone aggregates in the assessment. Additionally, lava stone aggregates were chosen over crushed expanded clay due to their high positive assessment of sustainability performance. Lava stones occur naturally, requiring only mechanical processes and not heat treatments before being used in concrete products.

Regarding mechanical properties, compressive strength is negatively affected by both types of aggregates compared with natural aggregates (Figure 3.5), with only SSA and BFS showing increased compressive strength results. However, SSA and BFS were not selected due to their low availability and economic allocation considerations. For freeze-thaw (FT) resistance, testing on porous concrete products could not be found to the best of the author's knowledge. Assessments based on conventional products indicate that RCA reduces FT performance compared with natural aggregates, while lava stone showed improved FT performance, although this conclusion was based on a 30% substitution rate and fine aggregates. As a result, conclusions for porous concrete remain unclear, and it is estimated that mechanical properties may decrease due to high porosity. This creates an additional knowledge gap that should be addressed for both types of aggregates chosen.

3.4. Admixture selection

Except for the typical materials incorporated in the concrete mix, other types of admixtures have been investigated and used in porous concrete in the building envelope and vegetation applications. The findings from literature are presented in Table 3.2.

As shown in Table 3.2, the admixture that is extensively used in the literature for porous concrete is water reducer in the form of plasticizer/superplasticizer. However, negative impacts on bioreceptivity performance have been found as shown in Table 3.2. On the other hand, SB latex is the most suitable additive to be used in the bioreceptive porous concrete mix as it enhances both mechanical and bioreceptive properties without reducing porosity. However, if used, it is recommended to keep its proportion low in the binder weight content due to sustainability concerns. This is why SB latex is a copolymer produced through emulsion polymerization of two different monomers: styrene and butadiene. Styrene is formed when benzene and ethylene react at room temperature, resulting in a colorless oily liquid with a sweet odor. Butadiene, on the other hand, is a byproduct of the hydrocarbon ethylene and is a colorless gas with a faint odor resembling gasoline [154].

Table 3.2: Type of admixtures used in the literature for porous concrete.

Type of admixture	Used in literature	Main use	Major conclusions
Water reducer/ plasticizer	[6] [38] [76] [78] [111]	Reduces water use of cement paste & improves strength.	Reduces void ratio & permeability, potentially impacting bioreceptivity of concrete mix.
SB latex	[71] [72] [140]	Enhances the bonds in the concrete product & the tensile strength.	Improves compressive strength & freeze thaw resistance. Enhances plant growth as it prevents leaching due to formation of a coating.
Jute fibers	[71] [72] [74]	Used as a reinforcing agent in cement.	Increases porosity but harms compressive strength. Enhances plant growth.
Alkali activators	[74] [40]	Use to form a geopolymer.	Increase of the activator, increases the alkalinity of the concrete mix that can potentially impact its bioreceptivity.

Final selection of admixture

For the selection of the admixture, the most important factor taken into account is market supply rather than sustainability performance, given that it is added in a small proportion to the concrete product and has a slight impact on the sustainability performance of the final product.

SB latex is not available in the EU market and is not preferred for industrial use due to its limited availability. As a result, superplasticizer is chosen to be added in a small percentage in porous concrete, as it is the most commonly used admixture and easily accessible. However, it is included in the concrete mix in the smallest proportion applicable due to its documented impact on decreasing void ratio and permeability, potentially affecting the bioreceptivity performance of the concrete product.

3.5. Final selection of concrete mix designs

3.5.1. Materials

Based on the multi-criteria analysis for binder and aggregate selection and the admixture selection, two mix designs are made for the bioreceptive porous concrete to be tested. The chosen binder for both mix design is Calcined Clay Cement (C^3), identified as a promising low-carbon substitute for cement in the future. However, its bioreceptive performance has not been tested, a gap that is important to study. Regarding the aggregate, two different aggregate types are going to be investigated, the one being recycled concrete and the other being lava stone, substituting the natural aggregate by 100%. Additionally, the incorporation of superplastizer as an admixture is opted with the lowest proportion used in the concrete product to not harm bioreceptivity negately. This is 0.4% of the binder content.

A reference mix is going to be tested for comparison reasons with the two different concrete mix designs. The composition is going to be OPC as the binder, given its prevalence in construction works. Aggregates used are natural crushed stone aggregates due to their frequent use in the civil infrastructure and mechanical properties as presented in Section 3.3.1. In addition, superplasticizer is used in this reference mix in the same proportion as opted for the two mix designs already proposed.

3.5.2. Water-to-binder ratio

Except for binder and aggregate selection, it is important to identify other important ratios for the concrete mix such as water which is one of the main parameters to be defined. In the case of the porous concrete mix, the water-to-binder ratio is proposed to be maintained between 0.25 to 0.45 [66] while it has been found that increasing the water-cement ratio from 0.25 to 0.35 rapidly increases compressive strength, with a lesser increase of 3% observed from 0.35 to 0.40 [65]. Based on these findings a water-to-cement ratio of 0.4 is proposed as the primary used and is further tested and adjusted through mortar samples (Chapter 4).

3.5.3. Aggregate gradation

In terms of aggregate gradation, porous concrete typically utilizes aggregate sizes ranging from 10 to 20 mm. However, increasing aggregate size can enhance porosity while decreasing compressive strength. Studies suggest that employing various fractions of coarse aggregates, rather than a single fraction, can increase the compressive strength of the porous concrete [66, 45, 70]. Considering the literature review in Chapter 2 and the results presented in Table 2.4 regarding the effect of aggregate size and gradation on porosity and compressive strength, a proposed gradation is between 8 to 16mm. The designed porosity of the concrete mix is 25%, a value appropriate for plant growth [40].

In Table 3.3 below, the final mix designs under study are presented.

Table 3.3: Concrete mix designs under study.

	Binder	**Aggregate Type**	**Admixture**	**Water-to-binder ratio**	**Aggregate Gradation**
Mix 1	C^3	Lava stone	Superplasticizer	0.4	8-16mm
Mix 2	C^3	RCA			Sieve up to 8mm.
Ref Mix	OPC	Limestone			Use sizes up to 22.4 mm
Proportion		100%	0.4% of binder content.	Further tested	Void ratio: 25%

4

Experimental set-up and materials

This chapter describes the methodology used to determine the concrete mix design, specifying the volume of each material in the concrete product. Section 4.1 starts with the determination of the aggregate properties used in the experimental mortar phase and concrete phase. Section 4.2 describes the method for identifying the final volume of materials used in the concrete samples through the mortar phase testing. Finally, in Section 4.3, the experimental setup for the concrete samples is described.

4.1. Aggregate properties

The properties studied for each aggregate are: the particle size distribution (PSD), particle density and water absorption. Comparisons between the properties of the aggregate types are provided.

Particle size distribution - PSD

- **Relevance:** PSD is used to determine the different aggregate fractions and their proportions in the concrete mix. It is an important property to measure as it influences the particle composition within the concrete mix. Aggregates are selected to be used in the 8-16 mm fraction. Fine material smaller than 8 mm is sieved out and removed.
- **Method:** The PSD is performed based on NEN-EN 933-1:2012 (E).

Water absorption and particle density

- **Relevance:** Water absorption of aggregates is an important property as it affects the amount of water that needs to be added to the concrete mix to ensure the right workability. It also impacts the compressive strength and durability of the concrete. On the other hand, particle density influences the mix proportions and the volume of aggregates in the concrete mix. Knowing the particle density allows for the efficient use of materials and reduces waste in the concrete product.
- **Method:** Both experiments are performed based on NEN-EN 1097-6:2022 (E).

The experimental results for the aggregates are presented in the following subsections. A full - description of the experimental set-up for defining aggregate properties is given in Appendix A.1.

4.1.1. Recycled concrete aggregates

Introduction

The recycled concrete aggregates used in the concrete mix under study are free from pollutants and other waste materials, making them high-quality recycled concrete aggregates that can positively affect the mechanical properties of the concrete mix design.

Particle size distribution

In Figure 4.1, the PSD of the recycled concrete aggregates is presented. The total aggregate material sieved was 5 kg and the sieving process was performed given the EU standard introduced. The PSD along with the sieve sizes (in grey) used are presented in Figure 4.1.

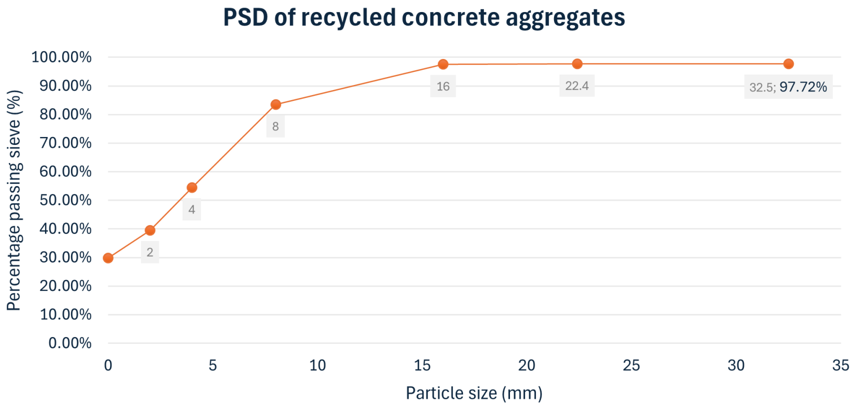


Figure 4.1: PSD of recycled concrete aggregates.

According to Figure 4.1, the recycled concrete aggregates contain a significantly high proportion of fine material, with nearly 30% of the total product passing through the smallest sieve particle size (less than 2mm). The largest proportions of particle sizes are observed for sizes exceeding 4mm, 8mm, and 16mm. Another important parameter that can be observed from Figure 4.1 is that the final percentage passing from the sieve is 97.72% and not 100%, showcasing the total water content of the recycled aggregates, equal to 2.28%.

Particle density and water absorption

The particle density and the water absorption of the recycled concrete aggregate are determined given the EU standard introduced. Density is calculated to be 2.584 kg/m^3 using the pyknometer method while the water absorption is 2.3% after 24 hours of immersion in tap water.

4.1.2. Lava stone aggregates

Particle size distribution

The lava stone aggregates are sieved at the same way as the recycled aggregates, using an equal amount of material. In Figure 4.2, the PSD of the lava stone aggregates is presented.

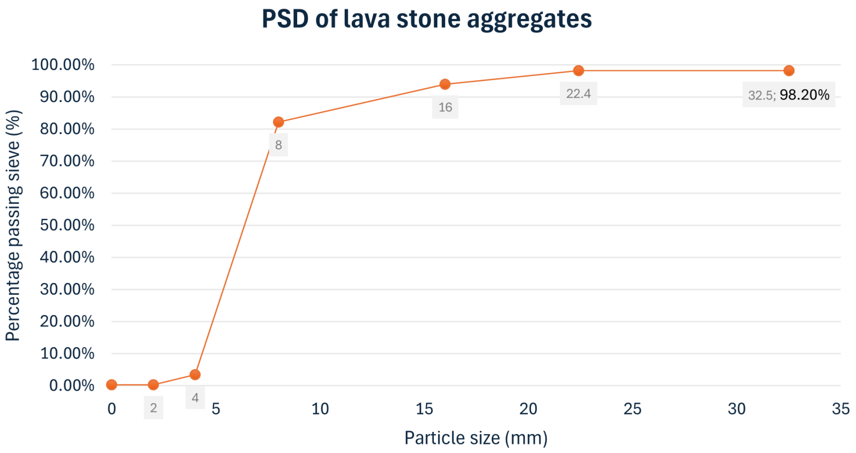


Figure 4.2: PSD of lava stone aggregates.

According to Figure 4.2, the lava stone aggregate has an extremely low content of fine sand, almost reaching 0%. The largest proportions of particle sizes are observed for sizes exceeding 8mm and 16mm. Additionally, the total water content for lava stone aggregates is slightly lower compared to recycled concrete aggregates, measuring 1.80%.

Particle density and water absorption

The density is calculated to be 2.400 kg/m^3, while the water absorption is found to be 4.6%.

4.1.3. Limestone aggregates

Particle size distribution

The limestone aggregates are sieved in the same way as the recycled aggregates, using an equal amount of material. In Figure 4.3, the PSD of the limestone aggregates is presented.

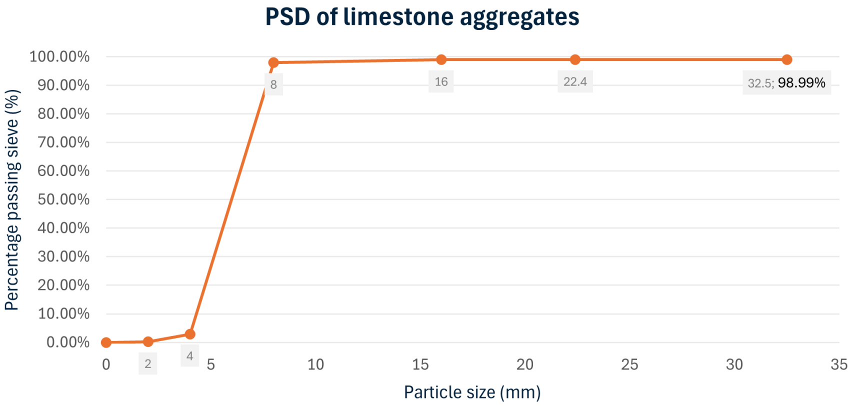


Figure 4.3: PSD of limestone aggregates.

According to Figure 4.3, the limestone aggregate has an extremely low content of fine sand, almost reaching 0%. The largest proportions of particle sizes are observed for sizes exceeding 8mm. Additionally, the total water content is only 1.00%, which was the lowest compared to the other two types of aggregates.

Particle density and water absorption

The density is calculated to be 2.662 kg/m^3, while the water absorption is found to be 0.5%.

4.1.4. Conclusions of aggregate properties

To achieve a particle size larger than 8 mm for the porous concrete mix under study, it is necessary to sieve the recycled concrete aggregates due to the presence of fine material (Figure 4.1). Thus, all aggregates are sieved, and density and water absorption are determined after the sieving process. Water absorption tests revealed that lava stone absorbed the highest amount of water (4.6%), followed by recycled concrete aggregates with nearly half the absorption rate (2.3%), and limestone with one-fourth the absorption rate of lava stone (0.5%). Regarding aggregate density, values are closely clustered, with limestone aggregates exhibiting the highest density, followed by recycled concrete aggregates and lava stone aggregates, within a range of 2.400-2.700 kg/m^3 as presented in Table 4.1.

Table 4.1: Aggregate properties

Aggregate type	Water content	Water absorption	Particle density
Recycled concrete	2.28%	2.3%	2.584 kg\m^3
Lava stone	1.80%	4.6%	2.400 kg\m^3
Limestone	1.00%	0.5%	2.662 kg\m^3

Water content differs for water absorption as it represents the amount of water already absorbed by the aggregates due to storage in an open facility and exposure to weather conditions. This indicates that the recycled aggregates were the most moist. On the other hand, water absorption describes the maximum amount of water that the aggregates can hold. The lava stone exhibited the highest water absorption, as expected based on the literature presented in Chapter 3.

4.2. Volumetric compositions for mix designs

After determining aggregate properties, the iterative process starts for identifying the volumetric comporosition of binder and water content in the mix designs studied (Figure 4.4). As a result, concrete mortars are made.

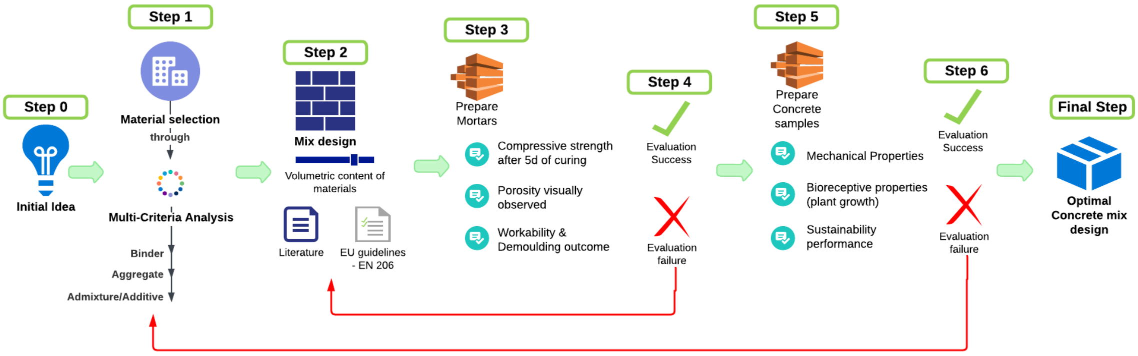


Figure 4.4: Iterative process for obtaining the volumetric compositions in the mix designs.

It should be noted that in the mortar phase instead of sand, the aggregates as described in Section 4.1 are used. This decision is taken given that the sand would result in different results in the workability and the compressive strength of the mortar sample compared with the concrete porous samples. The mortar sample making is presented in Appendix A.2.

To determine the volumetric composition for the mix designs, an iterative process is used as depicted in Figure 4.4. The initial step involves selecting the primary binder content based on EU guidelines and the literature review (discussed in Section 4.2.1). Concrete mortars are then created and tested for parameters such as compressive strength after 5 days of curing, visually observed porosity, workability, and demoulding outcome. Subsequently, a final binder content is chosen based on the results of each binder content tested, and the volumetric compositions for all mix designs are established. The criteria selection steps are outlined in the paragraphs that follow.

4.2.1. Binder content selection

Given the literature review and the studied mix designs in Chapter 2, along with the recommended limiting values for the composition and properties of concrete from EN 206:2013+A2:2021 (E), the first binder content is selected.

In the literature review, the binder content ranges from 280 to 350 kg/m^3. While the EU standard is usually applied to conventional concrete, the recommended limits for the composition and properties of concrete are also considered for porous concrete mix design. Different exposure classes are considered, and the use of reinforcement is also evaluated. Since the thesis does not consider any reinforcement, freeze-thaw attack is the only relevant exposure class for determining the binder content in the studied porous concrete mix design, particularly exposure class XF1. This class involves moderate water saturation without de-icing salts and mostly occurs on vertical concrete surfaces exposed to rain and freezing. The XF1 classification is chosen for vertical wall structures and concrete products studied because de-icing salts primarily impact horizontal surfaces. Vertical surfaces have minimal contact with salts, making them less susceptible to freeze-thaw damage due to de-icing salts, and the focus is given to freeze-thaw damage from water. The minimum binder content in this case is 300 kg/m^3, as depicted in Table F.1 of the EU standard NEN-EN 206:2014+A2:2021.

As a result, the tested binder content is 320 kg/m^3, supplemented by variations with higher (350 kg/m^3) and lower (290 kg/m^3) binder content.

4.2.2. Water content selection

Given that the literature suggests water content in the porous mix designs to be in the range of 0.25 - 0.45 [66], the highest water content was selected to be used and then adjusted during the mortar casting phase after checking the workability of the concrete mix.

During the mortar casting phase, the aggregates are pre-wetted. This decision is made because additional water needs to be added to each mix to meet the water absorption requirements of each aggregate. Adjustments should be made based on the water content characteristics of each aggregate type. Therefore, pre-wetting the aggregates 24 hours before casting could address issues with the workability of the mix design and remove the need to adjust the water content required for the aggregates.

In the following Table 4.2 the variations of binder and water content are presented. For all different binder contents the water-to-binder content remained stable in each casting phase of mortar samples.

Table 4.2: Binder and water content variations

Mix design	Binder content (kg/m^3)	Water content	Water content adjusted
Mix 1	290, 320 & 350	0.4	0.2
Mix 2	290, 320 & 350	0.4	0.3
Ref Mix	290, 320 & 350	0.4	0.25

4.2.3. Outcome

Among the three different binder content alternatives, only one is chosen to facilitate comparison between the studied mix designs. This decision is made after determining compressive strength of mortar samples after 5-days of curing and visually inspecting the porosity and void ratio. Finally, the volumetric compositions of the concrete products per m^3 are determined. The following paragraphs present the described steps.

Porosity

As already defined in Chapter 2, when binder content is increasing in porous concrete, porosity decreases and compressive strength increases. This already known result, is obvious in the mortar samples made. Binder content (290 kg/m^3) gives the best results in terms of porosity in all different mix designs as presented in Figure 4.5.

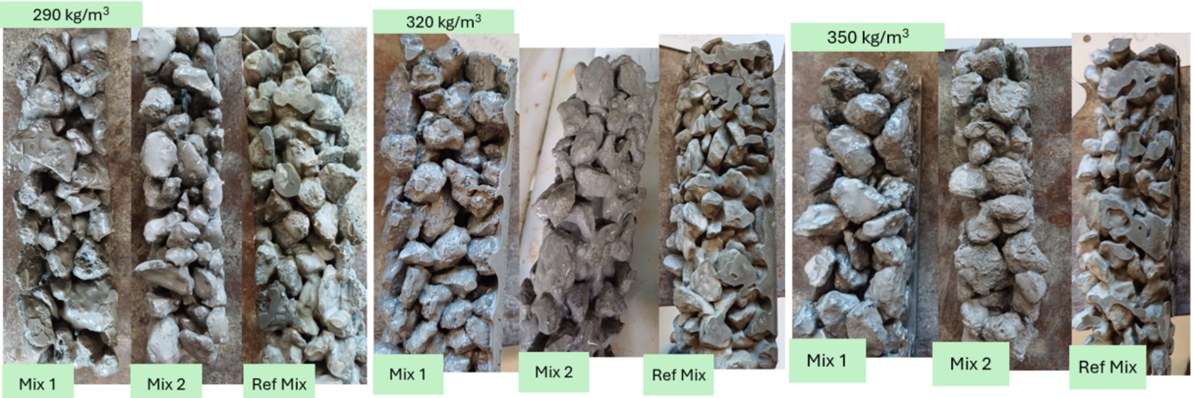


Figure 4.5: Representation of porosity of mortar samples.

Porosity is highly important in the studied mix designs because a higher void ratio potentially can facilitate the incorporation of the growing substrate. Porosity in concrete is influenced by the PSD and size of aggregate used in the mix designs. A notable finding given the PSD of the aggregate types, is that both recycled concrete aggregates and lava stone include a small proportion of aggregates larger than 16 mm, and even 22.4 mm, which increases the porosity of the mortar samples. On the other hand, limestone aggregates, with sizes mostly greater than 8 mm, harm porosity, resulting in a more compact mortar sample with binder. As a result, using the same binder content led to better porosity results for Mix 1 and 2, in comparison with the reference mix that includes limestone aggregates. These results will be further investigated by examining the porosity in the concrete samples in Chapter 5.

Compressive strength

- **Relevance:** The compressive strength of mortar samples is tested after 5 days of curing. By the 7th day of curing, concrete samples typically attain 60-70% of their 28-day compressive strength [155]. Due to the lab's availability during the testing period and the limited time to finalize the volumetric compositions before casting the final concrete samples, the 5-day compressive strength is used as a reference. This value helps estimate the compressive strength expected after 28 days, while also accounting for possible compressive strength results variations due to the differences between mortar and concrete samples, including their distinct testing surface areas.

- **Method:** The compressive strength test is performed based on NEN-EN 12390-3:2019 (E) and is further elaborated on Appendix A in Section A.4.

Regarding compressive strength, the higher the binder ratio, the higher the compressive strength. During the compressive strength measurements, it is found that the reference mix performed better across all binder contents studied, with values ranging from 9.6 to 11.2 MPa. Among the mix designs made with the C^3 binder, Mix 2, which used recycled concrete aggregates, achieved the highest compressive strength, reaching 3.10 MPa with the highest binder content studied. The lowest compressive strength is recorded for Mix 1 with lava stone aggregates, with values around 1 MPa. Figure 4.6 presents the compressive strength of the mortar samples after 5 days of curing.

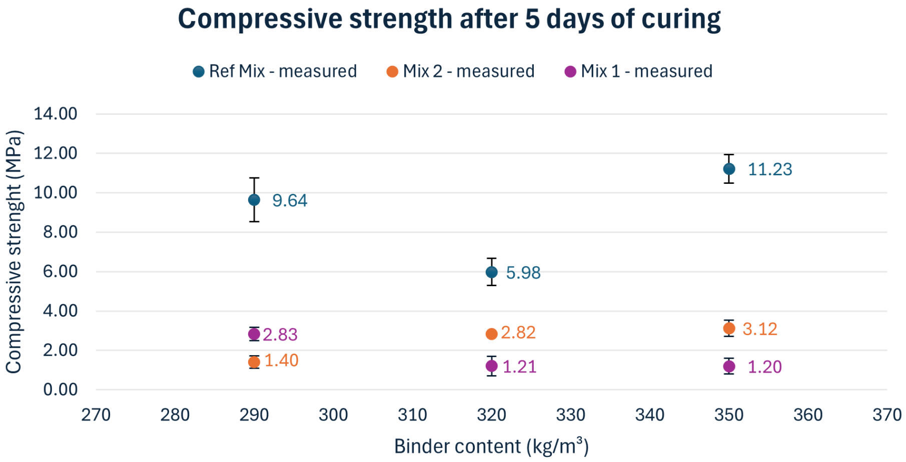


Figure 4.6: Compressive strength of mortar samples after 5 days of curing.

Based on the information in Figure 4.6, it appears that for binder contents of 320 and 350 kg/m^3, the differences in compressive strength between the various mix designs are minimal. Additionally, the difference in compressive strength between the lowest and highest binder content is between 1-2 MPa for all mix designs studied.

In addition, unexpected results were observed in the compressive strength of the mortars after 5 days of curing. Specifically, the compressive strength of the mortar with higher binder content (320 kg/m^3) in the Ref Mix was lower than that of the mix with lower binder content (290 kg/m^3). In addition, for Mix 1, the compressive strength with 290 kg/m^3 binder content was better than the compressive strength with 320 and 350 kg/m^3 binder contents. These results contradict the findings in Chapter 2, which suggest that higher binder content should lead to higher compressive strength.

It is suspected that either human error or machine error occurred during the measurement of compressive strength. Specifically, it is expected that the compressive strength of the ref mix should range between 9.64 and 11.23 MPa when the binder content is 320 kg/m^3. Similarly, for Mix 1, the compressive strength with a binder content of 290 kg/m^3 should be less than 1.20 MPa, as calculated from the maximum compressive strength of the higher binder contents of 320 and 350 kg/m^3.

Final selection of binder content

Based on the porosity and compressive strength results after 5 days of curing, the final decision regarding the appropriate binder content is made. However, the specific binder content used is not disclosed due to confidentiality reasons, and the exact volumetric compositions of the materials for each mix design per m^3 are documented in a confidential appendix.

Once the volumetric composition of the binder is determined, the volumetric proportion of aggregate is calculated based on the particle density. The proportion of the admixture is set at 0.4% of the binder content, and the final concrete samples are prepared.

4.3. Experimental set-up

This section describes the different types of tests conducted on the concrete samples, starting with the mechanical tests, followed by experiments for testing the substrate incorporation, bioreceptive tests, and plant growth germination tests. It focuses on describing the necessity of conducting each test and the method used to perform each experiment. If the test adheres to specific EU standards, the standard is referenced and the process is described analytically in Appendix A.3, along with the process for concrete sample making in Appendix A.2. In any other case, the process is described.

4.3.1. Mechanical tests

This subsection describes the tests performed to assess the mechanical properties of the concrete samples under study. All tests are performed after 28 days of curing in standard conditions with temperature 20 ± 2°C, and relative humidity >95%.

Compressive strength

- **Relevance:** Compressive strength is tested as it is the most important property to characterize a concrete product, evaluating the proposed mix design in terms of structural integrity. The limitation for the porous concrete mix design is 6 Mpa for non-load-bearing structures.
- **Method:** The compressive strength test is performed based on NEN-EN 12390-3:2019 (E).

Freeze-thaw resistance

- **Relevance:** Freeze-thaw resistance is tested to determine if the freezing and thawing cycles negatively affect the concrete mix proposed. Especially in the Netherlands, where temperatures in the winter are below 0, and freezing and thawing cycles occur is important to check the durability of the mix design due to weather changes, along with its performance after different FT cycles (2, 6, 14 and 28 FT cycles).
- **Method:** The freeze-thaw resistance is performed based on NEN-EN 12390-9:2016 (E), CDF test with no de-icing salts. The decision to use only water during the freeze-thaw resistance test is based on the exposure classes defined in relation to environmental actions according to EN 206:2013+A2:2021 (E). For freeze-thaw attack, four different classes are identified, with XF1 being the most appropriate to describe the use of vertical greening systems. This class applies to vertical concrete surfaces exposed to rain and freezing, with limited or no exposure to de-icing salts.

4.3.2. Growing substrate incorporation methods

In this section, the methods tested for the substrate incorporation are presented.

Introduction

Firstly, the ingredients included in the growing substrate are presented. It is made from potting soil, sieved to remove large wooden fibers, and a biological binder used to glue the soil into the pores of porous concrete. The volume ratio of soil to binder is 10:1, respectively. The available pore space for each 15x15x15 cm cube sample is determined by substituting the total volume with the binder and aggregate volume. The exact proportion of soil and biological substrate are used based on the available pore space, which calculated to be almost 1 L making soil volume equal to 970 mL and substrate volume equal to 97 mL.

Water pouring

- **Method:** This method is simple and practical for industrial use and is proposed by the Holcim Innovation Center in Lyon.
- **Process:** The process for incorporating the substrate involves mixing potting soil with water to create a paste-like consistency. Then, the binder is added. Finally, the growing substrate is poured onto the top surface of the sample, and water is manually added.
- **Test set-up figure:** In Figure 4.7 below, the process of the water pouring method is presented.

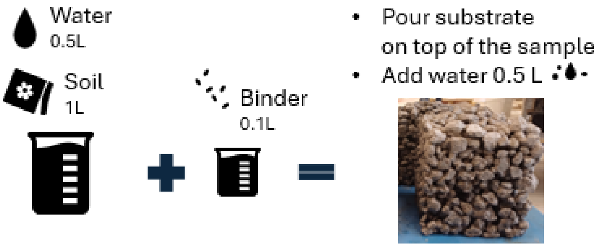


Figure 4.7: Process of water pouring method.

Water pouring with cotton cloth

- **Method:** This method is linked to the one already described, but it incorporates the addition of a cotton cloth to absorb the extra water and prevent the soil from escaping contact with the sides of the cube sample.
- **Process:** The process follows the steps described in the previous test. However, in this case, the concrete sample is covered on the four vertical sides and the bottom with the cotton cloth. The substrate is poured onto the top surface of the concrete sample, and water is added manually. After pouring the water, the sample is left to stabilize for 30 minutes. Once this time has passed, the cotton cloth is removed.
- **Test set-up figure:** In Figure 4.8 below, the process of the water pouring method is presented.

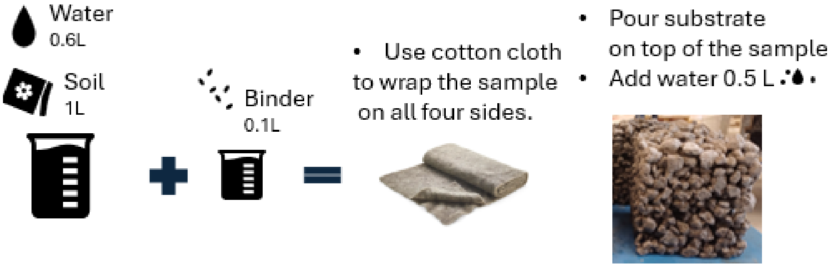


Figure 4.8: Process of water pouring method with cotton cloth.

Vacuum tank

- **Method:** Vaccum tank method is based on creating a low-pressure environment in which the air is removed from the macro-pores of the concrete sample, helping the growing substrate to adhere to the pores of the porous concrete sample. Different times of impregnation are tested.
- **Process:** The vacuum tank process varies depending on whether the wet or dry method is used. The main difference between the two methods is the addition of water in the mix. In the dry process, the soil and substrate are mixed and then poured into the vacuum tank until the concrete sample is filled with the substrate. Then impregnation begins, and different testing times are evaluated. A 10-minute impregnation proved to be inefficient as soil overflow from the pores of the porous concrete was observed [156]. Therefore, Meijvogel [156] suggested to reduce the suction time when conducting the vacuum tank test. It is true that when the surface pores are already filled with soil, prolonging the vacuum time does not yield different incorporation outcomes. Experimental trial times for the vacuum tank are 4, 5, and 8 minutes. In the wet process, water is incorporated into the substrate, requiring additional soil and organic binder. Upon observing that varying testing times had negligible effects on the vacuum test results—confirmed by measuring the weight losses on the substrate after vacuum tank treatment—a testing duration of 5 minutes is selected to validate this incorporation method for the wet process.
- **Test set-up figure:** In Figures 4.9 and 4.10 below, the process of the vacuum tank method -dry and wet- is presented respectively.

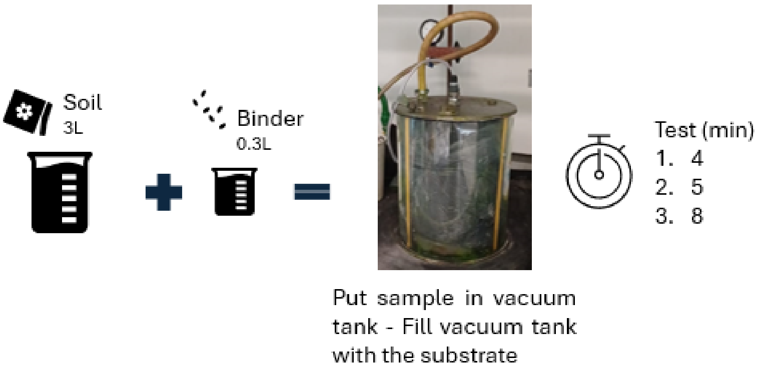


Figure 4.9: Vacuum tank - dry process.

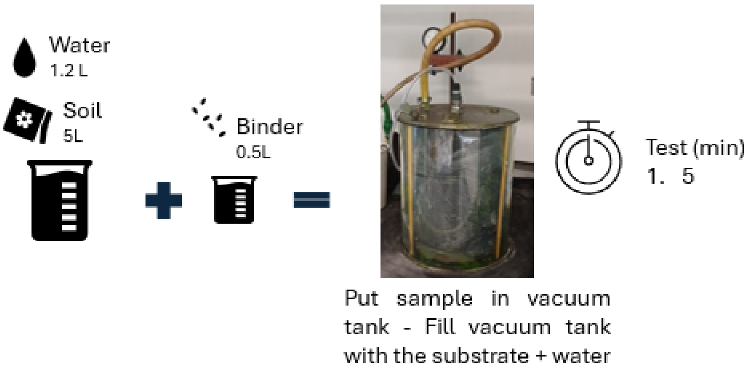


Figure 4.10: Vacuum tank - wet process.

After conducting tests to evaluate various methods of incorporating the growing substrate, cutting the samples in half is selected to assess substrate incorporation. This decision is made to determine the most effective method for the final incorporation of the growing substrate with plant seeds and validate plant growth. Results are presented in Chapter 5.

4.3.3. Bioreceptive tests

This subsection describes the tests performed to assess the bioreceptivity of the concrete samples under study. All tests are performed after 28 days of curing of the cube samples.

Porosity

- **Relevance:** Measuring porosity is important to verify if the intended void ratio of the concrete sample has been achieved and to understand how different types of aggregates affect the porosity of the concrete samples being studied. Additionally, interconnected porosity describes the amount of interconnected pores in concrete samples. It is linked to the available space left for soil incorporation, plant root development, and the movement of water and nutrients through the pores of the concrete sample.
- **Method:** The interconnected porosity is measured optimally using the following Equation 4.1 [157].

$$P = \left(1 - \frac{Ws - Ww}{\rho \cdot V}\right) \times 100\% \tag{4.1}$$

where: W_s is saturated surface dry weight (g), W_w is the weight under water (g), V is the volume of the sample (m^3), and ρ is the density of the water (g/m^3).

However, due to the absence of a hydrostatic scale in the laboratory, the volumetric difference method is used [158] for calculating open/interconnected porosity of cube samples.

- **Process:** The process for calculating the interconnected porosity is based on simply calculation of the volume displacement of water due to the immersion of the cube sample in the water.
- **Test set-up figure:** In Figure 4.11, the process of measuring interconnected porosity is presented.

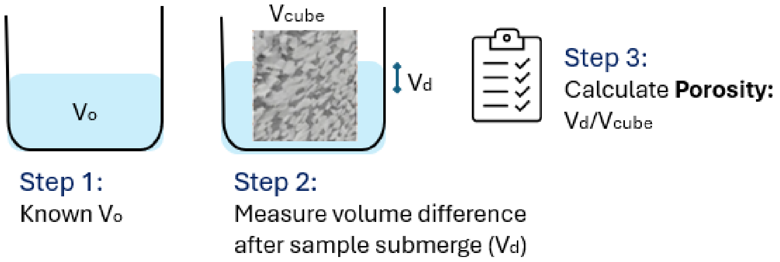


Figure 4.11: Porosity measurement method.

Alkalinity

- **Relevance:** Alkalinity is an important property to be measured, as pH influences plant growth. The pH of the root medium for plant growth should be kept below 10, and ideally below 9, to support plant growth [159]. Although the plants will not grow directly in the concrete but rather in the incorporated growing substrate, it is expected that leaching from the binder could influence the pH of the growing substrate. This might lead to a higher alkaline environment for the plants compared to what is defined by the growing substrate itself. Consequently, three pH values are determined:
  1. pH of the growing substrate (soil & organic binder)
  2. pH of the concrete samples
  3. pH of the interaction of the growing substrate with the concrete sample.
- **Method:** The method used for measuring the pH is adapted from Grant [160].
- **Process:** The process to measure the pH is categorized in three different methods as three different pH are measured.
  1. **Measure pH of the growing substrate:** The soil with the organic binder are mixed and 10 grams are used for the pH measurement. Distilled water in the proportion of the 20mL is added and the mix is let to settle for maximum of 5 minutes. Finally, the supernatant liquid is extracted and its pH is measured. Figure 4.12 below presents the pH test setup.

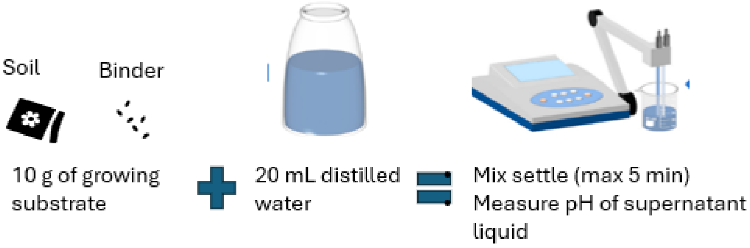


Figure 4.12: Test set-up for measuring pH of the growing substrate.

  2. **Measure pH of the concrete sample:** The concrete sample is broken with a hammer, and 10 grams are ground in a pestle and mortar. Then, distilled water is added in a proportion of 20 mL. The mixture is left to settle, and the pH of the supernatant liquid is measured. Figure 4.13 below presents the pH test setup.

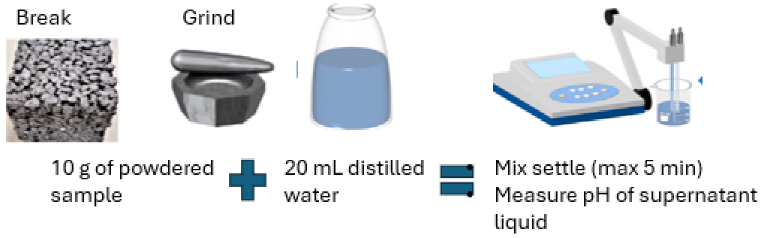


Figure 4.13: Test set-up for measuring pH of concrete sample.

3. **Measure pH of the interaction:** The soil used in the samples for testing plant growth is extracted in a proportion of 10 grams. This soil is incorporated into the concrete samples for 1 month. Then, the pH is measured using the same method as previously described. If the pH of the substrate changes, it indicates that leaching of the concrete elements has occurred. Figure 4.14 below presents the pH test set up.

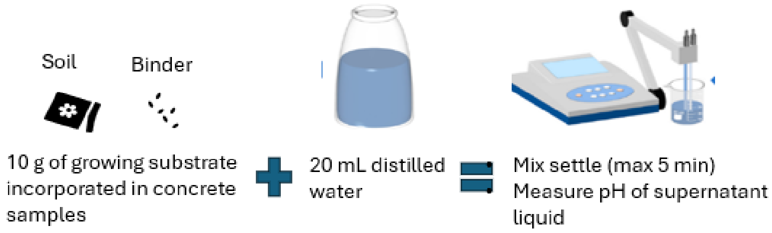


Figure 4.14: Test set-up for measuring pH of interaction.

Water absorption

- **Relevance:** Water absorption is an important parameter of the bioreceptive porous concrete samples as it can show indications of the maximum water that can be absorbed by the sample and given that the concrete sample is hosted plant seeds, water is important for their germination. The water that can be absorbed is measured with and without the growing substrate, to understand how the growing substrate can affect possitively this property. On the other hand, water absorption can also be linked with freeze and thaw as internal expanding water during a period of frost can lead to failure of concrete.
- **Method:** The method used for calculating water absorption is adapted from CROW [161].
- **Process:** The process begins by weighing the concrete samples and then drying them in an oven at 110 °C for 24 hours. The samples are weighed again after 24 hours, and the measurements are repeated until there is no weight difference between successive measurements. Once the samples reach a constant weight, the weight of the oven-dried samples is noted as W_d. Next, the samples are immersed in water for 24 hours to ensure complete saturation. The saturation process was extended to 3 days due to weekend days. The weight of the saturated sample is recorded as W_s. Finally, the weight difference between the fully dried and saturated sample will indicate the maximum water content that can be held within the sample.
- **Test set-up figure:** In Figure 4.15, the process of the water absorption method is presented.

Figure 4.15: Water absorption process.

Water retention

- **Relevance:** Water retention correlates with the maximum water absorption property of the concrete samples and determines how long water can be retained in a concrete sample and how many days it takes for the concrete product to fully dry. Water retention is measured after incorporating the growing substrate because the final medium in which the plant grows is a combination of the concrete product and the growing substrate.
- **Method:** The method used for calculating water absorption is adapted from CROW [161].
- **Process:** The water retention test begins after measuring water absorption with the growing substrate, after which a second drying process is carried out. The samples are placed in an oven until they are fully dried and no water is retained in the cube samples. At intervals of 1, 2, 3, 4, 7, 8, 9, 10, 11 and 14 days, the weight of the samples is measured.
- **Test set-up figure:** In Figure 4.16, the process of the water retention method is presented.

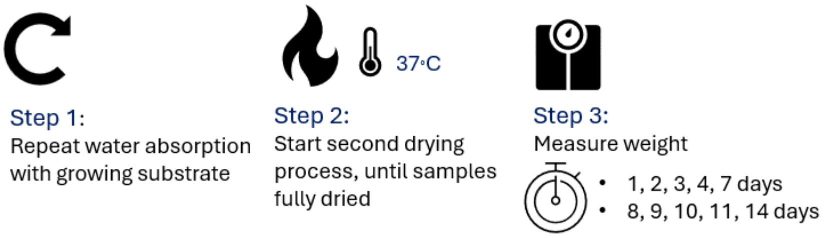


Figure 4.16: Water retention process.

4.3.4. Outdoor plant germination tests

This section describes the tests performed to assess the outdoor plant germination of the concrete samples under study. All tests are conducted after 28 days of curing of the cube samples and a 1-month germination period in the Hortus Botanicus of TU Delft.

Introduction

To test plant growth in the different mix designs studied, the growing substrate is incorporated using one of the methods presented in Subsection 4.3.2. Plant seeds are also incorporated into the growing substrate. Two types of seeds are selected because they have already been tested for quay walls in the Netherlands, specifically in Breda [162] and Delft [163]. These plant species naturally occur in various quay wall structures in different cities in the Netherlands [156]. The selected plants are Cymbalaria muralis and Erysimum cheiri.

Cymbalaria muralis is an example of a wall plant that often appears on quay walls in the initial weathering stage. In contrast, Erysimum cheiri is a climax species that only appears when the wall is severely weathered. Both wall plants can survive dry periods and thrive in environments with an alkaline pH. Additionally, these plants have relatively thin and weak roots, which limits the risk of mechanical damage to the concrete samples.

Three tests are performed to assess plant growth in the concrete samples studied as presented below.

Germination rate

- **Relevance:** Germination rate is tested to understand which mix design favors higher germination of plant growth. Conclusions for the mix design, binder and aggregate selection can be linked with the bioreceptivity performance of each concrete product.
- **Method - Process:** The same proportion of seeds for both plant species are incorporated in the growing substrate and after 1 month of germination period, the plants germinated are counted.

Plant stress

- **Relevance:** Plant stress is measured to understand how well the plant is growing. Plant stress is a biological response to challenging conditions that can negatively affect their health. The parameter Fv/Fm, defined as maximum potential quantum efficiency of Photosystem II, measures chlorophyll fluorescence, and assesses plant photosynthetic activity by measuring a plant's capacity to convert light energy into chemical energy, which can offer insights into its health [164]. Reduced values of Fv/Fm may indicate stress, photoinhibition, and downregulation of photosynthesis [165]. The Fv/Fm ratio for healthy, unstressed plants is typically around 0.79-0.84 [166]. It should be noted that Fv/Fm is linked with the environmental factors or conditions that the plants are exposed such as ambient temperature, relative humidity, CO_2 concentration, air current speed, and root zone temperature [167]. This should not pose a significant issue in this study, as all plants were grown under identical conditions in the same position at the Hortus Botanicus. While slight differences in humidity and temperature may have occurred due to placement under tree leaves, potentially affecting water exposure and sunlight, these variations are not expected to have a major impact on the results, given the close environmental conditions.

- **Method:** The chlorophyll fluorescence parameter is measured by PAM Chlorophyll Fluorometer after the plants have adapted to dark lights.
- **Process:** The process for measuring Fv/Fm is straightforward and is described in the following steps:
    1. Dark adapt each small plant for 20 minutes using small dark leaf clips.
    2. Take three Fv/Fm measurements for each sample.
    3. Repeat steps 1 and 2 for each of the three samples per mix design.
    4. Calculate each sample's average Fv/Fm ratio, then compute the overall average for each mix design.

Dry biomass

- **Relevance:** The germination rate of plants is linked to their dry biomass, which is measured by weighing the germinated plants after drying. The results help conclude the best mix design for germination rates and enable comparisons between different mix designs studied.
- **Method-Process:** The aboveground part of the plants is cut off. The plants are dried at 40 °C until the mass is stable. Then, the dry mass is recorded and comparisons between different mix designs are made.
- **Test set-up figure:** In Figure 4.17, the test setup for measuring dry biomass is presented.

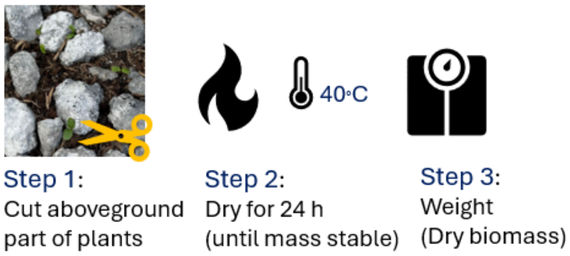


Figure 4.17: Test set up for measuring dry biomass of plants.

5

Experimental results

This chapter presents the experimental findings from all tests conducted on the concrete samples in the thesis. It begins with the representation of the mechanical properties of the concrete mix designs studied. Following, the different methods tested for incorporating the growing substrate into the pores of porous concrete and their outcomes are presented along with the bioreceptive results. Finally, the findings from outdoor germination tests are presented.

5.1. Mechanical properties

Mechanical properties tested for the concrete samples are compressive strength and freeze-thaw resistance after 28 days of curing as already described in Chapter 4 in Section 4.3. Compressive strength is also evaluated after assessing the bioreceptive properties of the mix designs, both with and without the substrate. The samples are subjected to drying at 105°C (3 days), immersion in water for full saturation (3 days), and then drying at 40°C for 2 weeks (14 days). The compressive strength testing is repeated 20 days beyond the standard 28-day curing period, resulting in a total testing duration of 50 days after casting.

5.1.1. Compressive strength after 28d of curing

Requirement

The minimum compressive strength required for non-load bearing walls is 6 MPa after 28 days of curing [168]. However, the strength requirement may vary based on the stakeholder's needs and can be either more or less than 6 MPa if a two-layer structure is used for the porous concrete product.

Results

In Table 5.1 below, the average compressive strength results are presented for the different mix designs studied.

Table 5.1: Average compressive strength results after 28 days of curing.

Mix design	Compressive strength	Standard deviation
Mix 1	2.48	0.14
Mix 2	2.91	0.15
Ref Mix	9.74	0.76

Based on Table 5.1, the Ref Mix design achieved an average compressive strength of nearly 10 MPa, satisfying the 6 MPa requirement. Mix 1 and Mix 2, on the other hand, reached approximately 2.5 MPa and 3 MPa, respectively, falling short of the compressive strength requirement. However, it may be feasible to use these mix designs in combination with a backing layer that can meet the strength requirements for wall construction. Potential uses for Mix 1 and 2 are discussed in Chapter 7 in Section 7.1.6.

The breaking points, as identified per each mix design, are presented in Figure 5.1 below.

Figure 5.1: Breaking points of concrete samples after compressive strength test.

Interpretation

A similar breaking pattern is observed. In all mix designs, the aggregates are breaking, including limestone, which typically has higher mechanical properties. However, as presented in Figure 5.1, Mix 1 and Mix 2 completely break during compressive strength testing. This highlights the brittle nature of both lava stone and recycled concrete aggregates used, likely due to their inner porous structure. The breaking point is concentrated in both the interfacial zone between the aggregates and the concrete paste and within the aggregate itself. This issue is compounded by the low binder content, which reduces the compressive strength. This suggests that the bonding between the binder matrix and the aggregates can be improved.

5.1.2. Compressive strength after drying process

Requirement

Compressive strength is reassessed after measuring the bioreceptive properties with and without the substrate, to understand how extreme humidity and drying conditions affect the compressive strength. This also allows for obtaining compressive strength results for the total concrete product, including the growing substrate.

Results

In Figure 5.2 below, the average compressive strength results are presented for the different mix designs studied across all testing periods."28d" refers to the compressive strength after 28 days of curing. "S-50d" indicates the compressive strength after 50 days of curing, including the growing substrate after water immersion and drying processes. "NS-50d" presents the same outcome as "S-50d" but without the incorporation of the growing substrate.

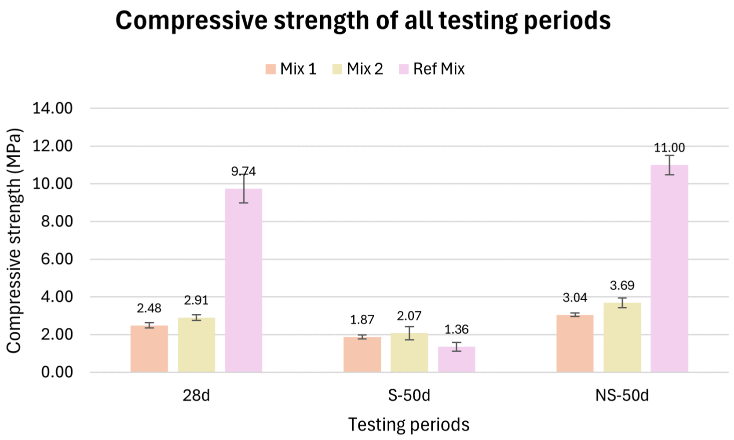


Figure 5.2: Average compressive strength of concrete samples for all testing periods.

In addition to Figure 5.2, Table 5.2 below, presents the average compressive strength results of all different testing periods and the percentage changes in the compressive strength.

Table 5.2: Average compressive strength of the concrete samples for all testing periods.

Compressive strength of all testing periods			
	28d	S-50d	NS-50d
Mix 1	2.48	1.87	3.04
Percentage difference		- 25%	+ 23%
Mix 2	2.91	2.07	3.69
Percentage difference		- 29%	+ 27%
Ref Mix	9.74	1.36	11.00
Percentage difference		- 86 %	+ 13%

As can be seen by Table 5.2, there is a common trend in the compressive strength results after the drying process. When the substrate is incorporated into the mix designs, compressive strength decreases after 50 days of curing, with the highest decrease in the Ref Mix. Conversely, when compressive strength is tested over the same period without substrate incorporation, compressive strength is increased for all mix designs, with the highest increase in Mix 2, followed by Mix 1 and the Ref Mix.

Interpretation

The significant decrease observed in the Ref Mix is interpreted based on two different processes occurring during the drying of a concrete sample. The following paragraphs provide an interpretation for both the increase and decrease in compressive strength.

- When concrete samples are heated at elevated temperatures, the effects of both microcracks and capillary pressure act on the concrete simultaneously [169]. Specifically, during the initial stage of drying, the water from the fully saturated concrete starts to evaporate in a quick pace, and the moisture content decreases [169]. This leads to the occurrence of microcracks either at the aggregate-mortar interface or perpendicular to the aggregate, ultimately resulting in a decrease in compressive strength [170]. As the drying process continues, capillary water begins to appear, and capillary pressure increases, acting as isotropic prestressing on the material. This leads to a stiffening effect, resulting in higher compressive strength at the end of the drying process [170]. This process is depicted in Figure 5.3 below.

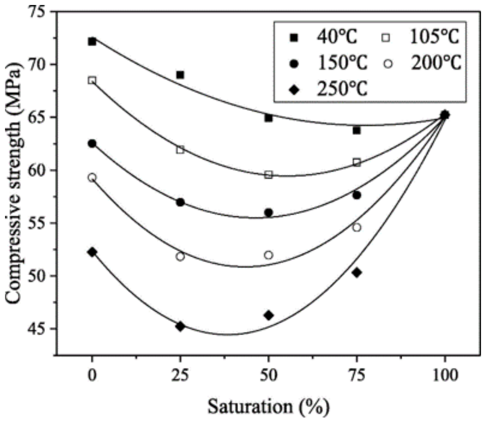


Figure 5.3: Effect of moisture content on compressive strength as depicted by Shen, et al. [169].

  Based on Figure 5.3, the changes in the compressive strength are depicted for concrete samples that are fully saturated and after drying at different temperatures. For both drying temperatures used in this research (40 and 105 °C), the compressive strength after drying is higher than in the saturated phase. This supports the argument of increased compressive strength after the drying process when no substrate was incorporated.

- The decrease in compressive strength is attributed to the effect of soil in the concrete sample, which acts as an insulator and affects the amount of water available to the capillary pores of the concrete. Consequently, the reduced water availability in the capillary pores, owing to the substrate, results in a decrease in capillary pressure. At this stage, microcracks have a greater impact on strength development than capillary pressure does. The greatest decrease in compressive strength is observed in the Ref Mix. This mix has the lowest porosity compared with the other mix designs (see Table 5.3), resulting in even lower capillary pressure. The lower capillary pressure leads to a reduced stiffening effect, ultimately resulting in lower compressive strength. To further explain this outcome, Scanning Electron Microscopy (SEM) is recommended to investigate microcrack propagation and further validate the justification proposed.

- It should be noted that the interpretation provided requires further testing. Specifically, samples from the same batch were tested for their compressive strength, and the decrease observed in the Ref Mix could also be linked to the specific design batch or sample preparation. New batches of the same mix design should be tested for compressive strength with soil incorporation after 50 days of curing. If the results align with the previously mentioned ones, this would support the relevance of the current explanation. SEM could then be used to further investigate microcrack propagation.

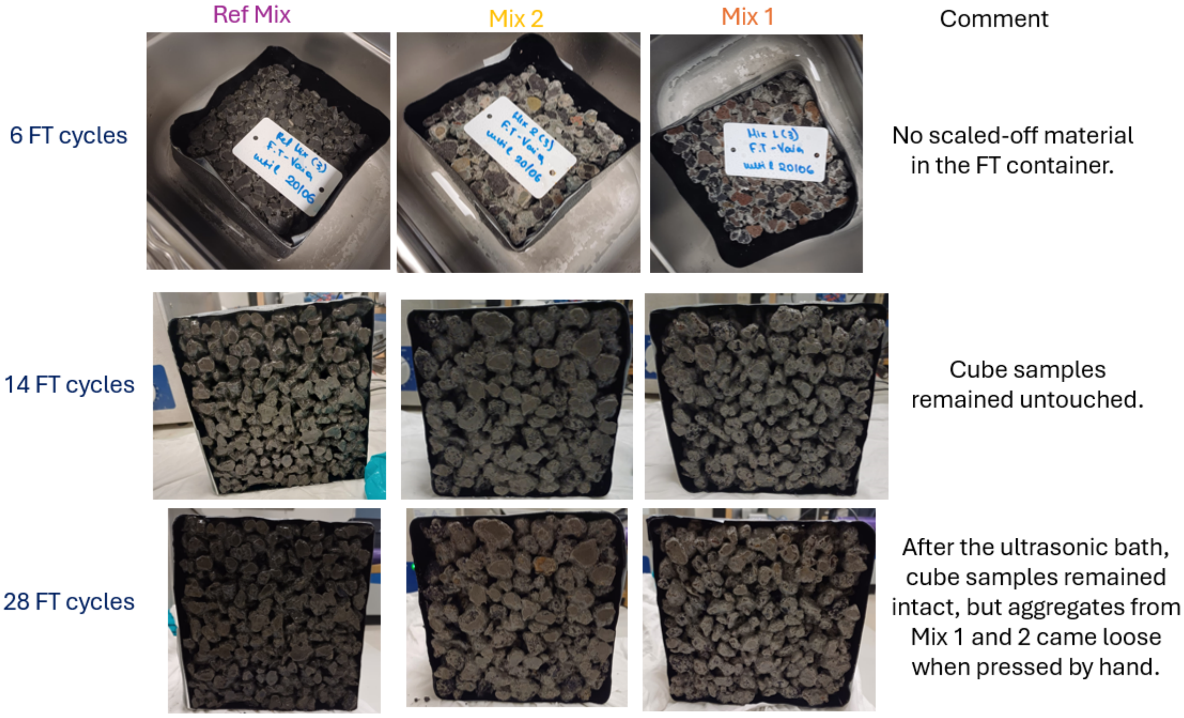
5.1.3. Freeze-thaw resistance

Requirement

There is no specific requirement for freeze-thaw resistance in the porous concrete samples, such as a specific mass loss rate that must be met after a certain number of freeze-thaw cycles (FT cycles). However, the samples are assessed for their scaled-off material after 2, 6, 14, and 28 FT cycles with no de-icing salts. If the samples break or aggregate falls off before the 28th FT cycle, the experiment is stopped.

Results

In Figure 5.4 below, the concrete samples are presented after each FT cycling testing period. The results after 2 FT cycles are not presented because the scaled-off material was negligible, and no pictures were taken during this cycle.



No scaled-off material in the FT container.

Cube samples remained untouched.

After the ultrasonic bath, cube samples remained intact, but aggregates from Mix 1 and 2 came loose when pressed by hand.

Figure 5.4: Freeze-thaw deterioration of studied mix designs up to 28 FT cycles.

In addition to Figure 5.4, the scaled-off material per unit area is presented in Figure 5.5 below.

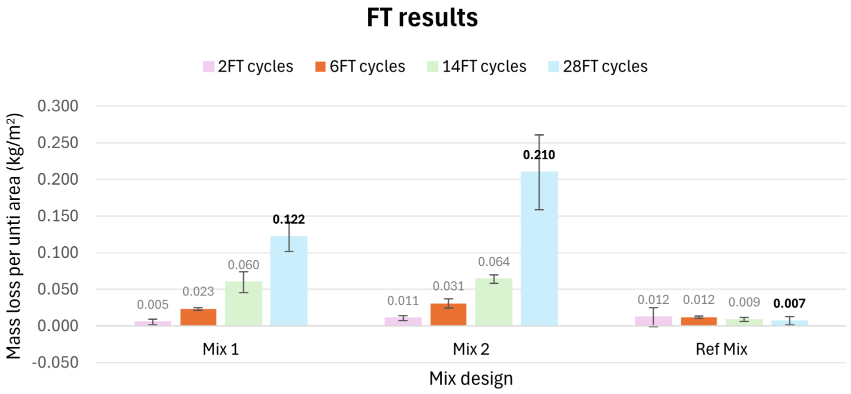


Figure 5.5: Average scaling of mix design studied.

All mix designs studied performed better than expected given their high porosity and low compressive strength, withstanding the 28 FT cycles. Among the mix designs, Mix 2 showed the worst performance in terms of FT resistance across all cycles, with a mass loss per unit area reaching approximately 0.21 kg/m^2 after 28 FT cycles. Conversely, the Ref Mix performed the best, likely due to its higher compressive strength and lower porosity compared to the other two mix designs. At the same time, a decreasing amount of scaled-off material was observed with an increasing number of FT cycles. This can be attributed to the fact that weaker parts of the samples were lost during the initial FT cycles, which led to a reduction in the weak areas of the cube samples in the later cycles.

Mix 1 and Mix 2 exhibit similar behavior in terms of scaled-off material: as the number of freeze-thaw (FT) cycles increases, the amount of scaled-off material also increases. This demonstrates the clear impact of freeze-thaw resistance on these mixes, with an increasing number of cycles resulting in greater mass loss and weakening of the concrete. Although the samples remained intact after 28 FT cycles during standard testing, pressing the aggregates by hand caused them to become loose. This suggests a potential decrease in compressive strength for both mix designs due to the freeze-thaw effect. In the samples of Mix 1 and Mix 2, microcracks were visible, and the aggregates became loose but did not break apart (Figure 5.6). These observations indicate that deterioration was concentrated in the interfacial transition zone between the aggregate and the binder. The reduced bonding force, likely due to the lower binder content, appears to have contributed to this localized failure.

Figure 5.6: Loosening of aggregates from Mix 2 after 28FT cycles.

Further investigation is needed to provide a final explanation for this result, including preparing samples and testing their compressive strength after various FT cycles.

Interpretation

Based on the results achieved after testing FT resistance, it is important to analyze the failure patterns associated with water exposure and connect them with findings from the literature on the freeze-thaw durability of porous concrete to further validate the reported results.

Starting with the mechanism of failure, different mechanisms have been reported in the literature, with the two most important being the hydrostatic pressure theory and the crystallization pressure theory. According to the hydrostatic pressure theory, the pores on the surface of concrete are filled with water. When the temperature drops below freezing, the water forms ice and expands in volume, pushing the unfrozen water into the surrounding capillaries. As the ice volume continues to increase, the unfrozen pore water in the capillaries cannot flow freely, causing hydraulic pressure to rise further. When the tensile stress on the pore walls exceeds the ultimate tensile strength, the pore wall structure ruptures, leading to the formation of microcracks [171], [113]. The crystallization pressure theory, on the other hand, suggests that frost damage in concrete is primarily caused by the pressure generated as ice crystals form and grow within the concrete's pores. The magnitude and direction of this crystallization pressure depend on factors such as pore shape, temperature, and the degree of ice formation. As ice crystals grow, they move from high-pressure areas to low-pressure areas, causing radial compressive stress on the pore walls. If this stress exceeds the material's tensile strength, it results in cracking and damage to the concrete [112].

In Figure 5.7 below, the different theories are depicted.

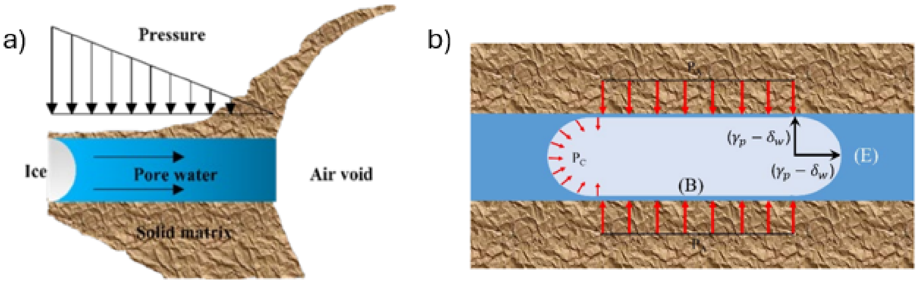


Figure 5.7: Failure mechanisms for FT damage with water: a) Hydrostatic pressure theory [112] and b) Crystallization pressure theory [112].

During FT cycling, concrete porosity increases proportionally with the number of cycles. Research has shown that characteristic parameters, such as pore size distribution and pore shape, change with FT cycles. Initially, the proportion of mesopores and macropores increases, while micropores continue to expand, leading to the formation of microcracks. These microcracks then grow into macroscopic cracks and larger pores. Early in the cycling process, pore structure deterioration occurs slowly. As the cycles progress and pores expand, water penetrates more completely, causing a rapid increase in concrete porosity. Additionally, the Interfacial Transition Zone (ITZ) between the mortar and the aggregate thickens due to the increased porosity induced by FT cycling (Figure 5.8) while the microcracks in the ITZ can account for more than 70% of the total matrix microcracks [112].

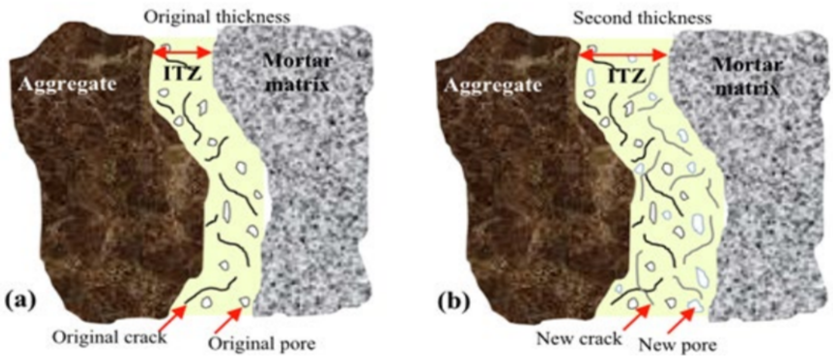


Figure 5.8: Deterioration mechanism of ITZ: a) original specimen and b) specimen under F/T cycle [172].

Regarding porous concrete, factors that further influence FT resistance include larger aggregate sizes and lower binder content, which can decrease bonding strength and increase susceptibility to FT deterioration [79]. Additionally, higher porosity creates more pathways for water to penetrate the concrete, leading to greater expansion forces due to ice formation and resulting in higher induced pressures that cause cracking [79]. This is supported by the thesis report results, where Mix 1 and Mix 2, which had larger aggregate sizes (up to 22.4 mm compared to up to 16 mm in the reference mix) and higher porosity (38% compared to 31% in the reference mix), exhibited greater mass loss per unit area.

Clear comparisons between Mix 1 and Mix 2 are possible since both mixes used the same binder, with differences in FT resistance attributed mainly to the types of aggregates used. Mix 2 exhibited greater deterioration, which can be attributed to the presence of multiple ITZs due to the inclusion of recycled concrete aggregate. These ITZs include old mortar-aggregate, new mortar-aggregate, and old mortar-new mortar interfaces. The presence of these multiple ITZs creates additional water movement channels, accelerates the deterioration process, and ultimately leads to more fine cracks [173].

To understand why the aggregates became loose after 28 FT cycles, despite the minimal mass loss observed in all mix designs, it is useful to consult relevant literature for further insight. Research has shown that even when cracks occur in samples during FT testing and bearing capacity is lost, the mass loss can be minimal or even negligible. This suggests that mass loss may not be a suitable metric for evaluating the freeze-thaw resistance of porous concrete [79]. To further validate this observation, consider the results presented by Xiang et al. [119], shown in Figure 5.9 below. Their study indicates that after 25 FT cycles with water, the mass remaining was nearly 100%, indicating no mass loss after the 25 FT cycles. This supports the findings of this research, where after 28 FT cycles, the mass loss for all mix designs was minimal (Mix 1 = 0.12%, Mix 2 = 0.19%, and Ref Mix = 0.01%). The mix design used in Xiang et al. [119] involved OPC with limestone aggregates sized between 2.5 and 10 mm, and contained a slightly higher amount of OPC per m^3 compared to the mix used in this thesis.

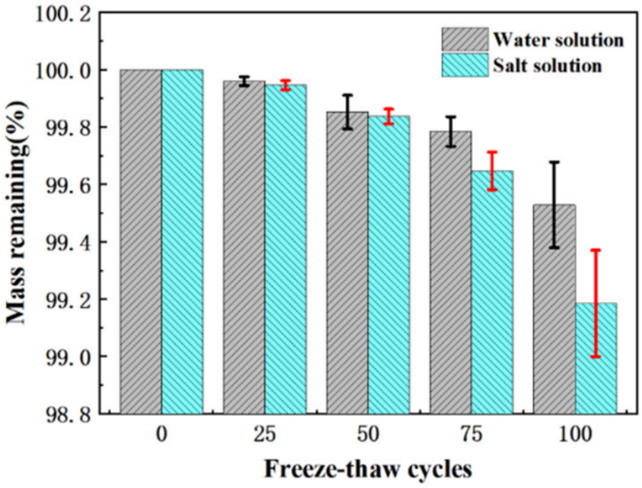


Figure 5.9: Mass remaining after FT cycles as tested and reported by Xiang, et al. [119].

Based on the results, it can be concluded that they align with existing literature. The FT resistance of the tested mix designs is promising, as all mixes successfully endured 28 FT cycles. However, additional validation is necessary due to the observed loosening of aggregates in Mix 1 and Mix 2 after the 28FT cycle. It is also important to note that mass loss may not be the most reliable measure of FT resistance for porous concrete, and the potential decrease in compressive strength requires further investigation.

5.1.4. Conclusions on mechanical properties

Overall, the mix designs studied for their structural integrity in terms of compressive strength and FT resistance showed promising results, given their high porosity and the brittle nature of the aggregates used (lava stone and recycled concrete aggregate).

Although Mix 1 and Mix 2 did not meet the compressive strength requirement of 6 MPa for non-load-bearing walls as reported in the literature, achieving nearly half of this strength (3 MPa) is promising and suggests potential with further improvements to the mix design, as elaborated in Chapter 7 in Section 7.3. Another interesting outcome is the compressive strength results when tested after 50 days with substrate incorporation and subjected to the drying process. The reduction in compressive strength for Mix 1 and Mix 2 was significantly lower compared to the Ref Mix, which decreased by almost 90%. This could indicate that the final concrete products of Mix 1 and Mix 2 with substrate have better compressive strength performance than the Ref Mix. However, further testing is needed to confirm this result and determine whether it is not due to a batch design issue.

Finally, all mix designs endured 28 FT cycles, which is a key finding given their high porosity and low compressive strength. This indicates that Mix 1 and Mix 2 possess a certain level of frost resistance, which is important for the durability and lifespan of the concrete product, as well as for reducing maintenance needs. However, the loosening of aggregates in Mix 1 and Mix 2 after 28 FT cycles suggests that further investigation is needed into their FT durability, specifically by evaluating other factors such as compressive strength loss after each FT cycle.

5.2. Growing substrate incorporation methods

5.2.1. Introduction

Different incorporation methods of the growing substrate in the concrete samples are tested as already introduced in Chapter 4 in Section 4.3.2. In the following subsection, the conclusion on the best method of incorporation is presented after cutting the samples in half with water cutting method. The representation of the results before and after the cutting method is presented below.

Depiction of concrete samples with the growing substrate: In Figure 5.10, the results after incorporating the growing substrate are presented. For each method, the representation of a cube sample is shown after the substrate incorporation.

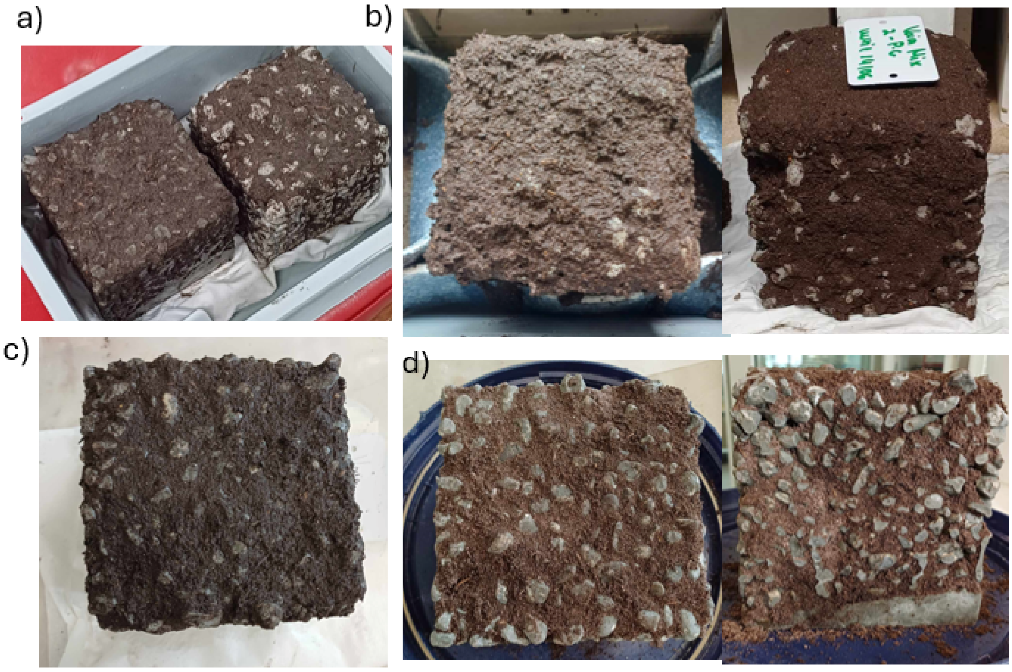


Figure 5.10: Incorporation methods of the growing substrate: a) water pouring, b) water pouring with cotton cloth, c) vacuum tank-wet process and d) vacuum tank-dry process.

Depiction of concrete samples after cutting: In Figure 5.11, the results after cutting the cube samples in half are presented.

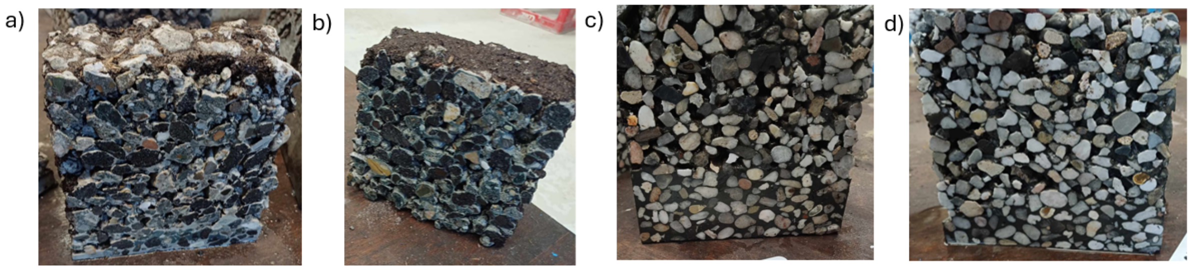


Figure 5.11: Cutting cube samples with substrate: a) water pouring, b) water pouring with cotton cloth, c) vacuum tank-wet process and d) vacuum tank-dry process.

5.2.2. Conclusions on growing substrate incorporation

Requirement

Given that the incorporation method of the growing substrate is identified as a knowledge gap, four different methods are tested. The optimal method is selected as the one that achieves the most effective distribution of the growing substrate in the pores of the porous concrete.

Conclusions

As presented in Figure 5.11, no method tested obtained the requirement as defined for the optimal incorporation method. This is why no method achieved to distribute the growing substrate in the pores of porous concrete, instead the growing substrate stayed on the surface of the porous concrete in the 4 sides and the top one, in which was poured.

Conclusions are:

1. None of the methods used allowed the growing substrate to penetrate the pores of the concrete cubes, and the substrate remained stuck on the surface of the cubes within 2-3 cm width.
2. The substrate used was sieved from large wooden fibers, and the soil was extra fine. However, when the surface pores were blocked, the soil could not penetrate deeper into the pores of the concrete product.
3. Even when water was poured using the wet cutting method a week after adding the growing substrate, the water did not cause the substrate to pour out of the sample, indicating that binder use acted as a glue. This property can be advantageous during rainy weather.
4. The wet process performed better than the dry process during vacuum tank tests. When the growing substrate was dry, the adhesive effect was weaker, leading to the loss of substrate from the concrete sample.
5. Even though the soil did not penetrate the pores of the cube samples, germination results were observed in the samples, as shown in Figure 5.12. This demonstrates a positive outcome in terms of bioreceptivity performance and could be attributed to the small roots of the plants used for plant growth, that do not need a high amount of soil for establishment and germination. Therefore, the presence of the available soil on the surface of the concrete could be beneficial for plant growth and does not hinder germination.

Figure 5.12: Preliminary germination results on Mix 2.

Outcome

Based on the conclusions presented, the chosen method for incorporating the growing substrate in the concrete samples to be tested for plant growth in the Hortus Botanicus is water pouring. This method was selected for its ease of execution and potential application in industrial settings. In the case of the cube samples, a cotton cloth is used to prevent the soil from being washed away by the water and to ensure that it remains in contact with the surfaces of all four sides of the cube sample.That is why cotton cloth is also used; however, incorporating cotton cloth into the wall structure is challenging and is typically used in smaller elements during experimental tests.

5.3. Bioreceptive properties

Bioreceptive properties tested for the concrete samples are porosity of the concrete product, water absorption with and without the growing substrate, water retention with the growing substrate, and alkalinity as already described in Chapter 4 in Section 4.3.

5.3.1. Porosity

Requirement

The interconnected porosity is measured to understand the amount of interconnected pores in concrete samples. The higher the porosity, the higher the space for roots and accumulation of water and nutrients needed for plant growth. The requirement is to achieve the designed void ratio and the minimum value accepted is 25%.

Results

The interconnected porosity is presented in Table 5.3 below.

Table 5.3: Average interconnected porosity.

Mix design	Porosity	Standard deviation
Mix 1	38%	3.1%
Mix 2	38%	2.2%
Ref Mix	31%	1.6%

All mix designs meet the 25% requirement, as shown by Table 5.3, demonstrating even higher porosity. Mix 1 and 2 are approaching 38%, which is considered a reasonable outcome considering the aggregates' PSD, where aggregate sizes up to 22.4 mm are used. The increased interconnected porosity can be explained by the non-homogeneous placement of aggregates during casting, further impacted by the lack of compaction that reduces air voids and ensures a uniform distribution of aggregates. Additionally, when designing volumetric proportions, factors such as aggregate angularity and surface modifications are not considered; instead, a homogeneous void ratio is assumed.

5.3.2. Alkalinity - pH

Requirement

For the alkalinity, the requirement is that the growing substrate, after incorporation into the concrete samples, does not exceed a pH of 9, as identified as appropriate for plant growth [159]. Since leaching of elements from the concrete products is expected and an increase in the pH of the growing substrate is anticipated, it is important to calculate the amount of increase to meet the aforementioned requirement.

Results

In Table 5.4, alkalinity is presented for growing substrate, concrete powder and their interaction after 1 month.

Table 5.4: Alkalinity measurements.

Alkalinity measurements				
Growing substrate				
Soil & organic binder	Alkalinity	6.51	Standard deviation	± 0.04
Concrete powder				
Mix 1	Alkalinity	11.01	Standard deviation	± 0.025
Mix 2		11.22		± 0.03
Ref Mix		12.50		± 0.05
Interaction of growing substrate with concrete				
Mix 1	Alkalinity	7.21	Standard deviation	± 0.015
Mix 2		7.53		± 0.025
Ref Mix		7.85		± 0.015

Interpretation

Based on Table 5.4, the growing substrate has the lowest alkalinity, close to 6.5, which is a typical value for soil substrates. Among the concrete powders of the different mix designs, the reference mix had the highest alkalinity measurement at 12.5, as expected since the alkalinity of OPC is in the range of 12-14 [40]. Mix 1 and Mix 2 resulted in lower alkalinity than OPC, as observed in the literature and discussed in Chapter 4 in the multi-criteria analysis of the binder as a choice criterion (Section 3.2) [90].

Finally, the interaction of the growing substrate with the concrete samples led to an increase in the pH of the growing substrate. This revealed the expected behavior of leaching of Na+, K+ and Ca-bearing compounds from the cement-based layer into the aggregate layer containing the growing substrate [68]. The leaching process is a result of diffusion processes after rainfall events or watering of the concrete blocks, which eventually promote pH changes in the growing substrate.

All substrate pH levels increased after 1 month of interaction with the concrete, with the highest increase identified in OPC. This is anticipated due to the higher pH of the reference mix, resulting in a greater change in the growing substrate pH after their interaction. Specifically, the percentage difference compared to the primary measurement of the growing substrate is depicted in the Table 5.5 below.

Table 5.5: Alkalinity measurements summary.

	Average pH of substrate after interaction with concrete (1month period)	Increase of pH compared with pH of the growing substrate
Mix 1	7.21	+11%
Mix 2	7.53	+16%
Ref Mix	7.85	+21%

According to Table 5.5, the lowest increase in substrate pH is observed in Mix 1 (11%), followed by Mix 2 (16%) and the Red mix (21%). This trend correlates with the pH measurements of the concrete powders, where OPC exhibited the highest alkalinity, followed by Mix 2 and then Mix 1, showing a linear trend between the alkalinity measurements of the concrete powder and the interaction of the concrete product with the growing substrate.

5.3.3. Water absorption

Requirement

For water absorption, there is no specific requirement to be achieved. However, the higher the water absorption capacity of the cube sample, the more water it can absorb. This affects plant growth, especially during the germination period when water is important. The water absorption is tested with and without the growing substrate, and the second outcome represents the real absorption of the final product. This is because the final porous product consists not only of the concrete but also of the growing substrate. It is expected that the concrete product with the added substrate can absorb more water compared to the concrete product without it.

Results

In Figure 5.13 below, the water absorption results are presented for all different mix designs, with and without the addition of the growing substrate.

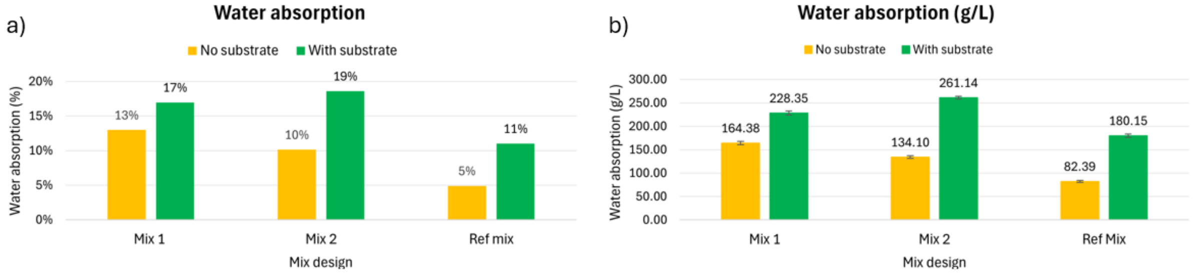


Figure 5.13: Water absorption with and without the growing substrate. Representation by a) percentage and b) g/L.

As can be seen by Figure 5.13 a, Mix 1 with lava stone has the highest water absorption at 13%, followed by Mix 2 with recycled aggregates (10%) and the Ref Mix (5%). Additionally, incorporating the growing substrate into the concrete sample results in higher water absorption, with both Mix 1 and Mix 2 reaching close to 18%, and the Ref Mix reaching almost 11%. The weight increase resulting from submersion in water per unit volume of each concrete sample is another way in which the water absorption results are displayed (Figure 5.13 b) . The water absorption results of the final concrete product with the substrate reached 228.35 g/L in Mix 1, 281.14 g/L in Mix 2 and 180.15 g/L in Ref Mix.

Interpretation

Results closely align with the expected outcomes. Mix 1 with lava stone aggregates exhibits the highest absorption capacity. This can be attributed to the highest porosity of the lava stone aggregates as discussed in the Multi-criteria analysis in Chapter 3 in Section 3.3. Mix 2 with recycled concrete aggregates exhibits the second highest water absorption capacity and it is explained again by the highest porosity of the aggregates compared with limestone.

The water absorption results when adding the growing substrate closely align with expectations. Porous concrete, with its high interconnected porosity, typically drains water quickly. However, the fine particle size of the growing substrate, combined with the organic binder's strong water-binding properties, blocks the pores, leading to increased water absorption. Consequently, water absorption increases by 4-8% across all the mix designs studied.

However, absorption in the case of porous concrete with the substrate is also dependent on the amount of substrate that becomes stuck in the pores of the porous concrete. In certain instances, the growing paste attaches to the surface of the porous concrete in a higher volume, yielding even greater results and further impacting water absorption. This can explain why Mix 2 shows higher water absorption outcomes compared with Mix 1 after incorporating the substrate as presented in Figure 5.13 and is further elaborated in Section 5.3.4 that follows.

5.3.4. Water retention

Requirement

When it comes to water retention, there is no specific requirement that needs to be met. The main goal is to understand how long concrete cubes remain moist without needing additional watering, especially to ensure the survival of plants during periods of low humidity. Water retention can be influenced by several factors:

- The volume of soil substrate incorporated into each mix design.
- The water absorption properties of different aggregates.
- The microstructure of the porosity of each aggregate type, particularly the presence and distribution of fine pores, and more specifically, capillary pores [3].

Results

In Figure 5.14 below, the water retention results are presented. The water evaporation ratio is depicted, with Figure 5.14 a showing the kilograms of water evaporated per day divided by the kilograms of water absorbed after immersion of the cubes. Figure 5.14 b represents the cumulative evaporation rate, showcasing the total water evaporated after 14 days of drying at 37 °C. The remaining water content after this period is also presented.

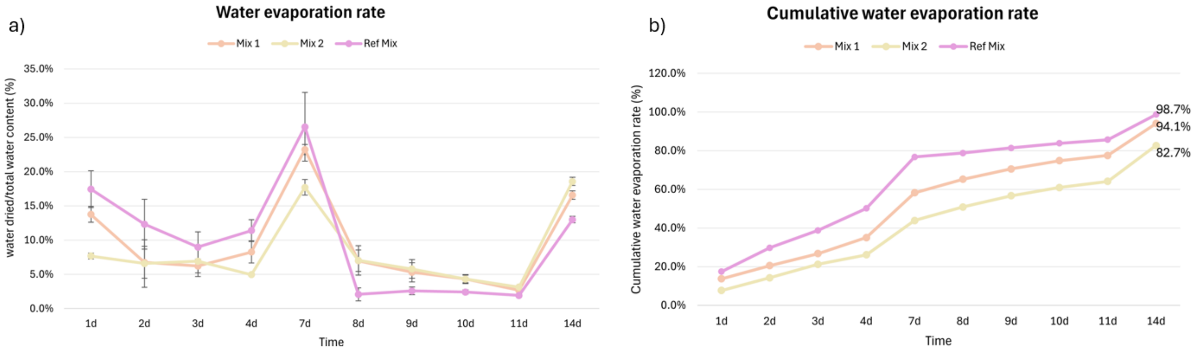


Figure 5.14: Water retention presented as a) water evaporation rate and b) cumulative water evaporation rate.

Interpretation

As depicted in Figure 5.14 a, most of the water is dried from the samples within the first day of the drying process, with subsequent days showing a decreasing trend in water loss. Peaks are observed around days forth to seven (4-7) and eleventh to fourteenth (11-14), although it should be noted that drying refers to 3 days.The general pattern observed is that the highest water loss is observed during the first day, with subsequent days showing a decrease in water loss.

Another important characteristic observed is that Mix 1 and the Ref Mix are losing a higher amount of water compared to Mix 2 during the first day, and this behavior continues until day 7. After that day, water loss from Mix 1 and Mix 2 stabilizes at similar levels, while for the Ref Mix, water loss decreases. This observation is further confirmed by the amount of water remaining in each mix design after the 14-day drying process. As can be seen by Figure 5.14 b, Mix 2 retains almost 20% of water after the 14 days of the drying process, while Mix 1 retains nearly 6%, and the Ref Mix is dried out at 99%.

This outcome may be due to the volume of the growing substrate incorporated into the different mix designs or to the microstructure of the aggregate porosity. The volume of growing substrate incorporated in each sample was intended to be the same, but variations can occur due to manual application, potentially resulting in a higher volume of fine substrate in certain concrete samples, which could further justify the final result. This observation can also be linked to the water absorption results obtained when the substrate was incorporated, as shown in Figure 5.13, where it was found that Mix 2 absorbed the highest amount of water compared to all other mix designs. This contrasts with the water absorption results without substrate incorporation, where Mix 1 showed higher absorption compared to Mix 2.

Interconnection of water absorption with retention results

Water absorption and retention results are estimated to be affected by the volume of growing substrate incorporated into the concrete samples. Consequently, an investigation was conducted to determine if this was indeed the case. The weight of the growing substrate incorporated into all samples was measured both before (MS) and after drying (DS). However, this weight does not correspond to the final weight of the substrate due to losses occurring during the incorporation and drying processes.

Since weight loss measurements were not recorded at the time, different estimates were considered. Specifically, losses during the incorporation process (IP) were estimated to be in the range of 5-20%, while losses during the drying process (DP) ranged from 5-15%. The final weight measurements of the substrate incorporated into the mix designs are presented in Figure 5.15 below.

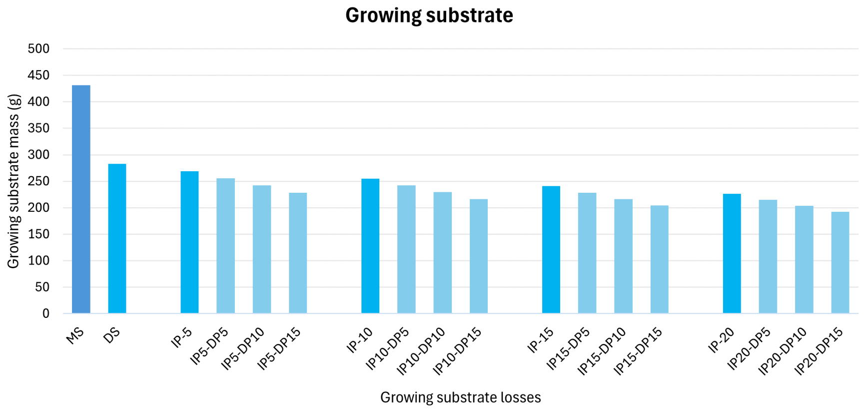


Figure 5.15: Growing substrate mass incorporated in the concrete product.

In the worst-case scenario, considering the highest loss rates for both the incorporation (20%) and drying (15%) processes (IP20-DP15), the weight of the substrate used is calculated to be 192.4 g. To assess the weight of the substrate used, the difference between the dried samples with and without the substrate was measured. The results are presented in Table 5.6 below.

Table 5.6: Average dried substrate incorporated per mix design in grams.

Average substrate (g) incorporated per mix design					
Mix 1	189.3	Mix 2	233.3	Ref Mix	197.5

Based on Table 5.6, it is evident that Mix 2 has the highest substrate content, followed by Ref Mix and Mix 1. This supports the initial hypothesis that the substrate volume affects water absorption and retention. Further explaining why water retention on Mix 2 was the highest after 14 days (Figure 5.14) and why water absorption after substrate incorporation increased and even surpassed that of Mix 1, which, when no substrate was incorporated, showed higher absorption rate (Figure 5.13).

Outcome

The outcomes for water retention and absorption with the growing substrate can provide indicative values but are influenced by the substrate volume and incorporation method, leading to variability from sample to sample. The initial goal was to incorporate the substrate within the concrete pores, taking advantage of the high porosity as a key feature However, none of the incorporation methods tested successfully embedded the substrate within the pores (Section 5.2.2), resulting in the substrate remaining on the surface and making the incorporation process inconsistent. This process can also be affected by the interconnected pores on the surface of the concrete samples. In some samples, the interconnections could help the substrate adhere to the surface, but this depends on the aggregate connection during casting, which is difficult to control. Overall, while water absorption and retention results can provide some indicative information about the concrete product with the growing substrate, variations in the results may occur due to changes in substrate volume, and are not able to characterize each mix design.

5.3.5. Conclusions on bioreceptive properties

Overall, the bioreceptive properties of the mix designs were consistent with existing literature. In terms of alkalinity, leaching of compounds from the concrete into the growing substrate increased the substrate's pH, with the highest increase observed in Ref Mix, followed by Mix 2 and Mix 1. This trend is closely related to the pH of the concrete powder, as a linear relationship was observed: higher powder pH resulted in a greater increase in substrate pH after one month of interaction.

Water absorption without the growing substrate aligns with literature findings, as Mix 1, which used lava stone aggregates, demonstrated higher porosity due to the higher porosity of the aggregate. Additionally, the volume of substrate incorporated affects the final results of water absorption and retention in the concrete products, with variations due to incorporation and drying process losses.

Finally, all mix designs met the design void ratio requirement of 25% and even exceeded it, largely due to the high aggregate gradation used, particularly in Mixes 1 and 2 (up to 22.4 mm). This was compounded by the lack of compaction and the non-homogeneous interconnection of aggregates during the casting phase.

5.4. Outdoor plant germination testing

In this section, the plant growth results are presented during the one month of outdoor germination testing in the TU Hortus Botanicus. It should be noted that watering of the plants occurred once per week during rainy weeks and twice per week during drier periods. Since the plants sown are drought-resistant, there was no need for watering more than twice per week. In Figure 5.16 below, the plant growth results are presented for each week of the testing period. Week 1 is not included because germination of the plants had not yet started.

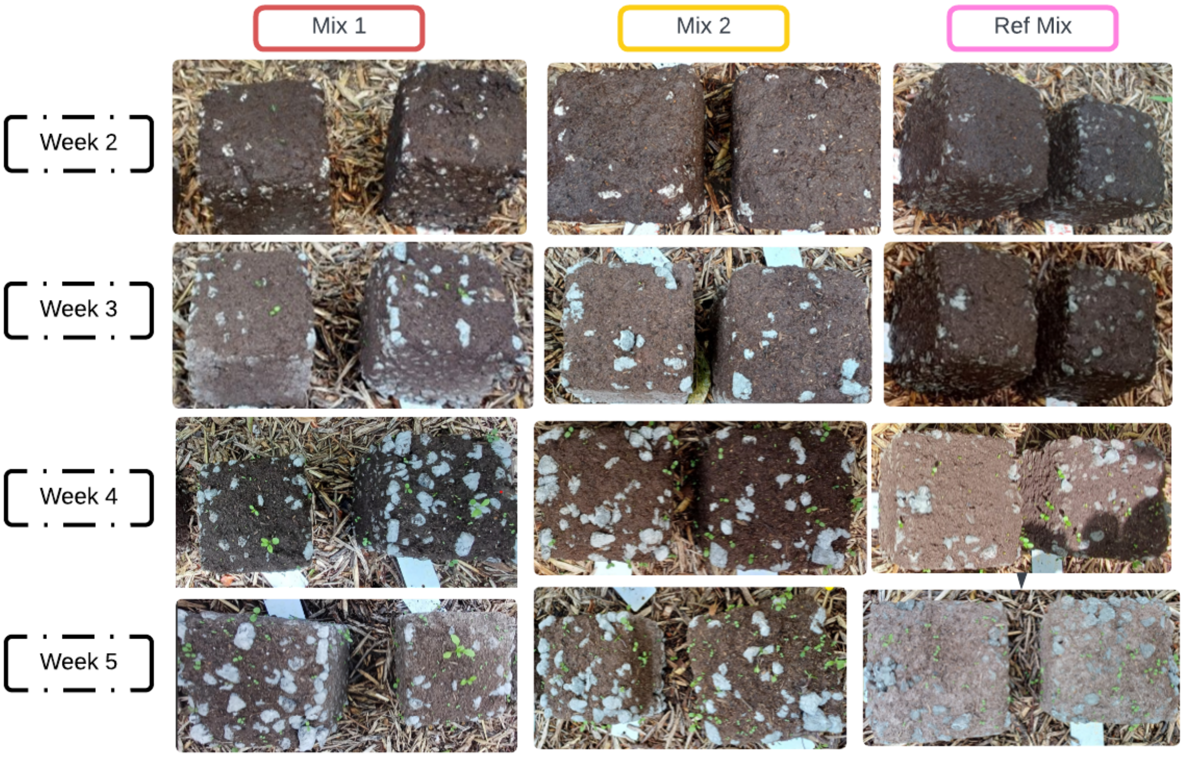


Figure 5.16: Plant growth results presented per week during the 1 month of testing period.

As can be seen by Figure 5.16, all samples tested resulted in the germination of the seeded plants. Mix 1 exhibited the fastest germination, and the tallest root height was observed after five weeks of observation. The results of plant germination are assessed based on the following parameters: germination rate, plant stress, and dry biomass are presented in Figure 5.17 and 5.18 respectively.

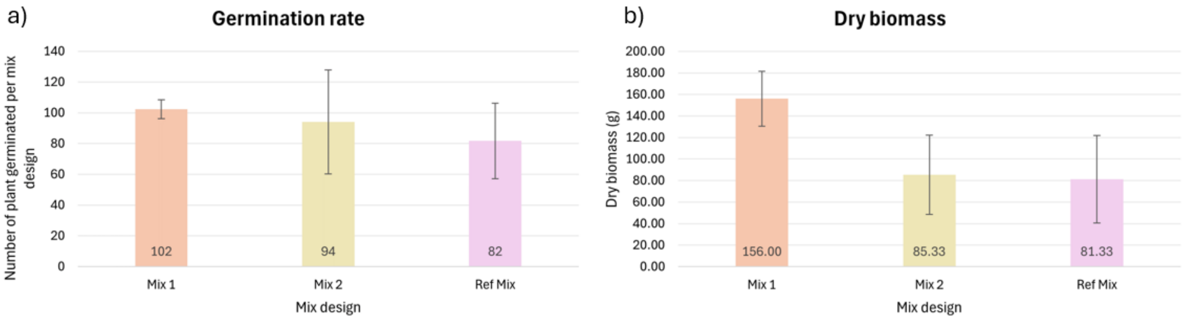


Figure 5.17: Plant growth results: a) germination rate and b) dry biomass.

Figure 5.18: Plant stress of germinated plants.

5.4.1. Interpretation

Germination rate

According to Figure 5.17 a, a higher number of germinated plants were counted in Mix 1, followed by Mix 2 and the Ref Mix. Another notable observation is that Mix 1 is the only mix design where the variance in the number of germinated plants is low, indicating consistent plant germination performance across all three samples tested. In contrast, the other two mix designs show significant variation in germination outcomes between samples. Specifically, one sample from Mix 2 achieved the highest germination rate, highlighting significant variance in the germination results across the different samples tested. This variance suggests that the results are not statistically significant, indicating the need for further testing to validate the germination rate and understand the factors contributing to the high variability between samples.

Dry biomass

As can be seen by Figure 5.17 b, the highest dry biomass was observed in Mix 1, which was expected due to its quicker germination and taller root height, resulting in increased dry weight compared to the other mix designs. Even though Mix 2 exhibited the highest germination rate in one sample, its dry biomass was lower than that of Mix 1. This lower biomass is related to the delayed start of the germination period and shorter root development in Mix 2. Specifically, samples from Mix 2 began germinating after Week 3, resulting in smaller plant roots height. A similar pattern was observed for the reference mix, where germination also started after Week 3, explaining the lower dry biomass compared to Mix 1. Variance in all mix designs was higher, as the germination height per sample varied and was not consistent. Even in Mix 1, where germination began earlier than in the other mix designs (starting after Week 1), different germination times were observed across the samples, with two of them germinating earlier, explaining the variance in dry biomass within Mix 1. Even if the germination rate was higher in some samples (such as one sample from Mix 2), the dry biomass could still be lower, indicating a delayed germination period and shorter root lengths.

Plant stress

As can be seen by Figure 5.18, the average ratio of Fv/Fm calculated for all mix designs ranges from 0.7 to 0.8, with Mix 1 exhibiting the highest ratio, followed by Mix 2 and the Ref Mix. Variations in plant stress were observed, with the Ref Mix showing higher variability among the plants measured per sample. This can be explained by the fact that during the measurement of the Fv/Fm ratio in the ref mix samples, some plants appeared dried, less fresh, and curling inward.

Overall, all three mix designs exhibit a ratio within the range of 0.79 to 0.84, which is typically associated with healthy, unstressed plants [166]. Although the average ratio for the Ref Mix is slightly lower at 0.73, it is still within an acceptable range and does not indicate significant plant stress. It should be noted that the conditions under which the samples were tested for germination were consistent in terms of environmental factors (ambient temperature, air current speed, CO_2 concentration, and relative humidity). This uniformity helps explain why the plant stress values among the different mix designs were similar. However, slight variations in the values could be influenced by differences in water exposure and sunlight, as the samples were placed under tree leaves in different positions. These varying conditions (microclimates) could contribute to the observed differences in germination rate and biomass.

5.4.2. Conclusions on plant growth

Among the different mix designs studied for their bioreceptivity performance in terms of plant growth, Mix 1 showed the most promising and consistent outcomes across all three properties studied (germination rate, dry biomass, and plant stress) among the different samples.

Mix 2 exhibited the highest germination rate in one of the samples, but there was significant variability in both germination rate and dry biomass across the different samples. A similar high variance was observed in the Ref Mix samples, indicating that the results lack the desired robustness and consistency. Further testing is required to understand the germination outcomes and the factors influencing the varying germination rates and high variance. Factors that could have affected the germination rate are likely related to outdoor conditions such as moisture availability, temperature, and seed predation. No direct connections can be drawn between the water absorption and retention results and the plant growth outcomes, as the growth tests were conducted on samples with varying volumes of growing substrate, which has previously been shown to impact these bioreceptive properties.

Fluctuations in dry biomass can be linked to the germination rate. Some samples among the different mix designs germinated earlier than others, resulting in taller plants and consequently higher dry biomass. These variations are connected to the period that the germination started.

Finally, all plants appeared to be unstressed, with Fv/Fm ratios close to the values reported in the literature for unstressed plants. The small differences in plant stress between the mix designs are attributed to the placement of samples in different positions, which introduced microclimates with varying moisture and temperature levels. However, the similarity in results is expected, as there was no significant variance in environmental conditions, given that all samples were placed in the same area for germination without altering the surrounding environment.

In Chapter 7, the plant growth results are thoroughly discussed, considering the high variance between the samples and how the experimental setup could be modified to better understand the reasons behind these variations in plant growth results.

Overall, the mix designs demonstrate great potential for plant growth, with Mix 1 showing consistent performance across different samples and proving to be the most optimal for plant germination. Additionally, it is important to note that the plants tested were selected for their drought resistance, tolerance to more alkaline environments, and small root systems, making them well-suited to adapting to the concrete environment without damaging the concrete product. These factors should be considered when discussing the plant growth results.

6

Life Cycle Assessment

In this chapter, the sustainability performance of the concrete products is evaluated using the Life Cycle Assessment (LCA) method. The chapter begins with an overview of the LCA method and its stages, followed by the assessment of the sustainability performance of the different concrete products (Section 6.2). The final conclusions and comparisons between the mix designs are presented in Section 6.3, followed by the recommendations in Section 6.4. In the final section 6.5, the optimal concrete mix design is determined after evaluating the mechanical and bioreceptive results (Chapter 5) in conjunction with the LCA results for the mix designs presented in this chapter.

6.1. Brief introduction in LCA method

A Life Cycle Assessment (LCA) is a method used to evaluate the environmental impact of a product throughout its entire life cycle, from raw material extraction to end-of-life scenarios and final disposal. In the Netherlands, evaluating environmental impact is traditionally accomplished using a final Environmental Cost Indicator (ECI), which quantifies the environmental burdens of a product in monetary terms. This approach simplifies product or service comparisons by translating environmental impact into monetary units in Euro (€), also known as shadow costs. These costs represent the damage that a product causes to the environment and indicate the amount of money needed to compensate for this damage using available technology. To conduct an LCA according to the European standard NEN-EN-ISO 14040 and NEN-EN-ISO 14044, four main phases must be defined and studied as depicted in the following Figure 6.1 [83].

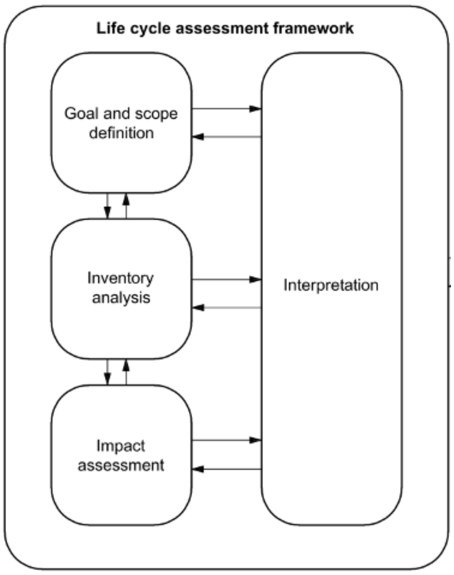


Figure 6.1: LCA framework based on ISO 14040 [83].

According to Figure 6.1, the first phase of the Life Cycle Assessment (LCA) includes both the goal and the scope of the assessment. The goal is connected with the intended use of the LCA, its purpose, and the intended audience. Regarding the scope of LCA, it is essential to define the Functional Unit (FU) of the assessment, followed by establishing the system boundaries of the LCA. The definition of the FU is crucial as it serves as a reference unit for quantifying and comparing the environmental performance of different products. The system boundaries provide information on the stages included in the assessment. Apart from these two crucial steps, it is also important to define assumptions, limitations, and data acquisition methods used when performing the LCA method.

The inventory analysis primarily involves selecting data for the inputs and outputs of the assessed products, including raw material extraction, electricity usage, gas consumption, and other energy inputs throughout the product's life cycle. Following, the impact assessment phase quantifies the environmental impacts of products using various environmental indicators as defined in NEN-EN-ISO 15804 for the Environmental Product Declaration (EPD) for the category of construction products. Specifically, during the impact assessment phase, the calculation of the final Environmental Cost Indicator (ECI) is the main outcome where the impact of each different material or stage during the life cycle assessment is translated into monetary values. The interpretation phase is the final stage of the LCA process, where the results are analyzed, and conclusions are drawn about the most impactful material used in a product or the most impactful stage in the LCA assessment. Additionally, comparisons are made between different products, and the results are visually presented for better understanding. Recommendations are also given to improve the environmental performance of a product or service.

In Chapter 6.2, the LCA method is employed to calculate the shadow costs of the suggested concrete mix designs. For each mix design, the results of the ECI value, along with comparisons, conclusions, and recommendations, are presented. All phases of the LCA method, as introduced, are conducted, beginning with the identification of the goal and scope, followed by the inventory analysis, impact assessment, and concluding with interpretation.

6.2. LCA for concrete mix designs

Goal of the LCA

The goal is to compare the ECI of the different concrete products developed to identify the one with the lowest shadow costs and to understand which stage in the life cycle of each product has the most significant environmental impact given the system boundaries that are going to be defined later in this section.

Scope of the LCA

The scope of the present LCA is to evaluate and compare the environmental impacts generated by the different concrete products studied for their bioreceptivity performance, consisting of variable types of binder and aggregates. The intended application of the performed LCA is TU Delft and the industry. The concrete mixes for LCA quantification are presented in Table 6.1 that follows.

Table 6.1: Concrete mix designs to be evaluated with LCA method.

Mix #	Binder type	Aggregate type	Addditive
Reference	OPC	Limestone (100%)	Superplasticizer
C^3-lava	C^3	Lava stone (100%)	Superplasticizer
C^3-recycled	C^3	Recycled concrete (100%)	Superplasticizer

System boundaries: Regarding the system boundaries, the LCA focuses on the production stage of the concrete product, specifically from stages A1 to A3. Stage A1 covers the extraction of raw materials (half-products for the concrete product), including energy and water consumption, as well as diesel consumption. Stage A2 involves the transportation of the half-products to the final manufacturing site of the concrete product. The manufacturing site is Holcim's production facility in Oudenbosch. Stage A3 involves the final manufacturing process of the concrete product, including energy and diesel consumption.

The research's system boundaries are chosen to concentrate on the concrete product and determine which materials used in the concrete product lead to higher environmental burdens as the primary focus is on the mix design rather than the construction phase. The different phases in the LCA method along with the system boundaries selected for this thesis are presented in Figure 6.2.

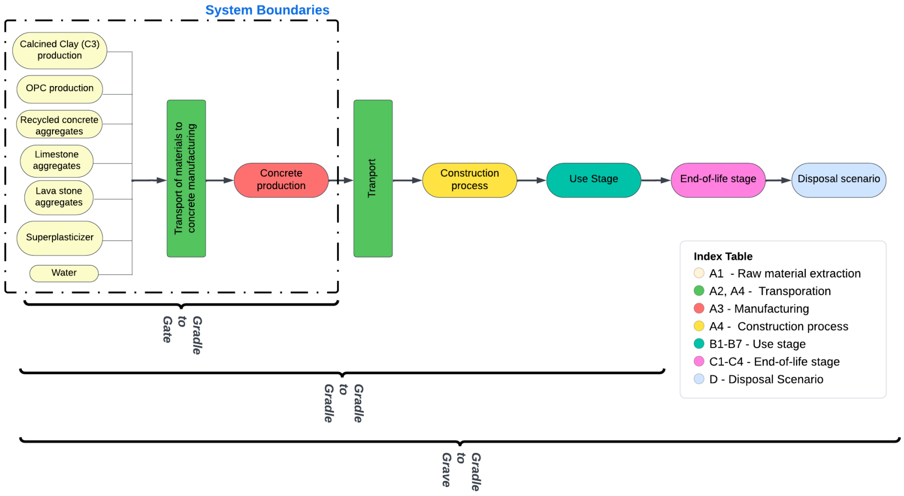


Figure 6.2: LCA system boundaries.

Functional Unit: The functional unit (FU) focuses on the production stage of **1 m^3 of concrete.** Given that the materials used in concrete mix designs vary per scenario, no specific strength or durability properties are specified for the FU.

Environmental impact indicators: Environmental impact indicators for assessing each concrete product are selected based on the EU standards EN 15804+A1:2013 and EN 15804+A2:2019 [83]. The primary difference between these two standards lies in the environmental indicators used to address the shadow costs of products and services. Specifically, EN 15804+A1 includes 11 impact indicators, while EN 15804+A2 includes 13 core impact indicators and 6 additional ones that consider damage to human health, ecosystems, and resource availability. EN 15804+A2 is the new standard for the LCA method. However, EN 15804+A1 is still in use due to the transition phase required for adjusting the previous indicators to the new ones.

The reported outcomes are based on EN 15804+A1, as the ECI value of the C^3 binder is only available according to this EU standard. Therefore, comparisons between the different concrete products would not accurately represent the total ECI indicator if the new standard was used. In the following Table 6.2, the environmental indicators as defined by EN 15804+A1:2013 are presented.

Table 6.2: Environmental impact categories based on EN 15804+A1:2013.

Environmental impact indicators			
Impact category	***Abbreviation***	***Equivalent Unit***	***Weighting factor [€/kg eq.]***
Abiotic depletion potential-non-fossil resources	ADPE	kg SB eq.	0.16
Abiotic depletion potential-fossil resources	ADPF	kg SB eq.	0.16
Global Warming Potential	GWP	kg CO2 eq.	0.05
Ozone layer depletion	ODP	kg CFK-11 eq.	30
Photochemical oxidant formation	POCP	kg C2H4 eq.	2
Acidification	AP	kg SO2 eq.	4
Eutrophication	EP	kg PO4 eq.	9
Human toxicity	HTP	kg 1.4-DCB eq.	0.09
Freshwater aquatic ecotoxicity	FAETP	kg 1.4-DCB eq.	0.03
Marine aquatic ecotoxicity	MAETP	kg 1.4-DCB eq.	0.0001
Terrestrial ecotoxicity	TETP	kg 1.4 DCB eq.	0.06

After defining the environmental impact indicators to be used for the mix designs, the LCA method is performed for the different mix designs and the reference mix. The outcomes for the ECI value, along with comparisons, conclusions, and recommendations, are presented in the following subsections.

6.2.1. LCA reference concrete

Full product description

The reference mix design, which is being studied for its environmental performance, is primarily used for comparison purposes with the developed mix designs. As previously discussed, the material selection was made to create a reference mixture using the most common materials found in a concrete product. It is anticipated that the ECI value of the reference mixture will be higher than that of the developed mix designs. In the following Figure 6.3, the process tree for the reference concrete mix is presented, including the transportation method used for each half-product along with the energy used for the manufacturing phase.

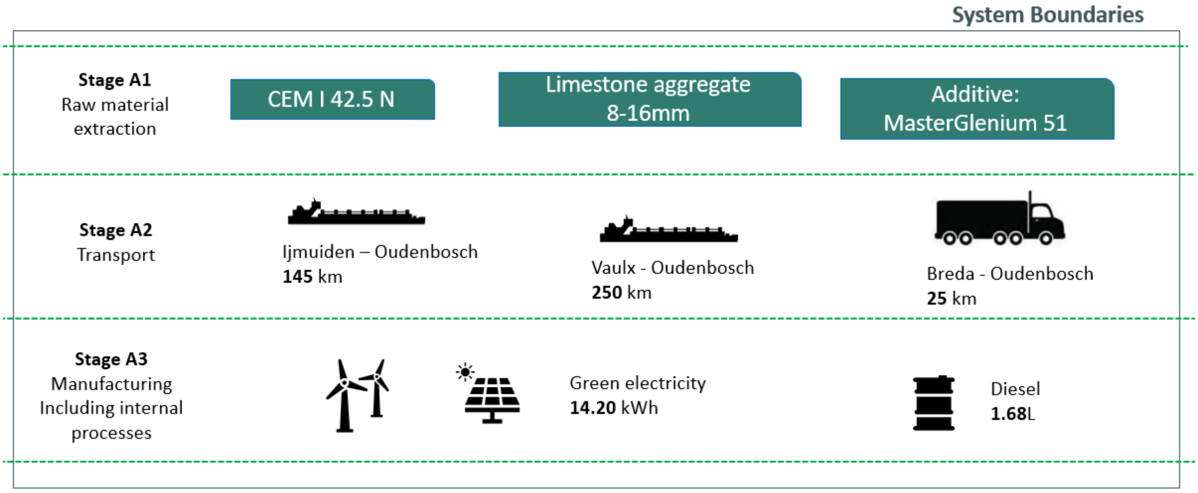


Figure 6.3: Process tree for reference concrete mix.

Elaboration on the process tree

Ordinary Portland Cement - CEMI 42.5N: The binder used for the reference mix is typical Ordinary Portland Cement and is being produced by a company in Ijmuiden, transported by an inland vessel in the production site of Oudenbosch at a distance of 145 km. Environmental data are retrieved from Ontwerptool Groen Beton v7 with environmental profiles:

1. Binder: CEM I 42.5 N (G1), ENCI / HeidelbergCement, c1 - NMDv3.5
2. Transportation: Transport, freight, inland waterways, barge RER | market for transport, freight, inland waterways, barge| Cut-off, U

Limestone aggregate: The limestone aggregate is supplied by a quarrying site in Vaulx in Belgium, and transported by an inland vessel at a distance of 250 km. Environmental data are retrieved from Ontwerptool Groen Beton v7 with environmental profiles:

1. Aggregate: Kalksteen (BE): Limestone, crushed, for mill CH| production | Cut-off, U / BE
2. Transportation: Transport, freight, inland waterways, barge RER | market for transport, freight, inland waterways, barge| Cut-off, U

Additive: The additive that is being used in the mix is supplied by a company in Breda, a common superplasticizer used for the production facility in Oudenbosch. The superplasticizer is being transported by truck at a distance of 25 km. Environmental data are retrieved from Ontwerptool Groen Beton v7 with environmental profiles:

1. Superplasticizer: Polycarboxylates, 40% active substance RER |market for polycarboxylates, 40% active substance |Cut-off
2. Transportation: Transport, freight, lorry, unspecified GLO |market group for transport, freight, lorry, unspecified |Cut-off, U.

Water: The water that is being used during the production of the concrete mix is not taken into account as the environmental burden for its addition is relative small, not impacting the final ECI results. At the same time, no transportation is needed as it is supplied by the facility in Oudenbosch.

Manufacturing stage of 1m^{3}of concrete product: During manufacturing of 1m^3 of concrete product, green electricity consisting of solar energy, wind energy onshore and offshore along with diesel consumption is being used in the composition of 14.20 kWh and 1.68 L respectively. Environmental data are retrieved from Ontwerptool Groen Beton v7 with environmental profiles:

1. Solar energy: Energy - Electricity (solar)
2. Wind onshore: Energy - Electricity (wind turbine, 1-3MW turbine, onshore)
3. Wind offshore: Energy - Electricity (wind turbine, 1-3MW turbine, offshore)
4. Diesel: Energy - Diesel (Diesel, burned in building machine GLO |market for| Cut-off, U)

Total production waste is determined to be 1.2% and is accounted for in the calculations of the total environmental impact. This waste is deposited as sludge.

LCA results

For the calculation of the ECI value, the proportion of each material (in kg) per m^3 of concrete product is used, but this information, along with the detailed ECI breakdown across LCA stages (A1-A3), is not reported for confidentiality reasons.

The life cycle impact analysis for the reference mix based on EN 15804+A1 standard is presented in Table 6.3 below.

Table 6.3: LCA of reference mix.

Environmental category	A1-A3
Abiotic depletion potential, non fuel	6.20E-05
Abiotic depletion potential, fuel	9.89E-02
Global warming potential	1.43E+01
Ozone layer depletion	2.48E-04
Photochemical formation	1.04E-01
Acidification	2.32E+00
Eutrophication	1.05E+00
Human toxicity	1.67E+00
Freshwater aquatic ecotoxicity potential	1.31E-02
Marine aquatic ecotoxicity potential	1.54E-01
Terrestrial ecotoxicity potential	2.54E-02
Total ECI	**€ 19.78**

Results and interpretation

The final ECI value, based on EN 15804+A1, is calculated to be €19.78. The most impactful stage in terms of shadow costs is the raw material extraction stage, with the binder material having the highest ECI value. In the transportation stage, higher material quantities transported over longer distances result in higher ECI values. In this case, the limestone aggregates constitute the highest proportion and involve one of the longest distances traveled. Finally, in the manufacturing stage, diesel usage incurs the highest ECI cost.

Regarding the environmental category most affected by the production of 1m^3 of the reference mix concrete product, GWP accounts for the highest ECI value, followed by AF and HTP, with a significant decrease in the ECI value. This makes GWP the most impactful environmental category. For the production of this concrete product, 286 kg of CO_2 are emitted, with the highest proportion attributed to binder production (stage A1).

6.2.2. LCA Calcined clay with lava stone

Full product description

The mix developed with the low carbon calcined clay binder is being evaluated for its environmental performance, as one of the purposes of the developed mix design is to achieve a mix with better sustainability performance and lower environmental footprint. In the following Figure 6.4, the process tree for the mix of calcined clay with lava stone is presented, including the transportation method used for each half-product along with the energy used for the manufacturing phase.

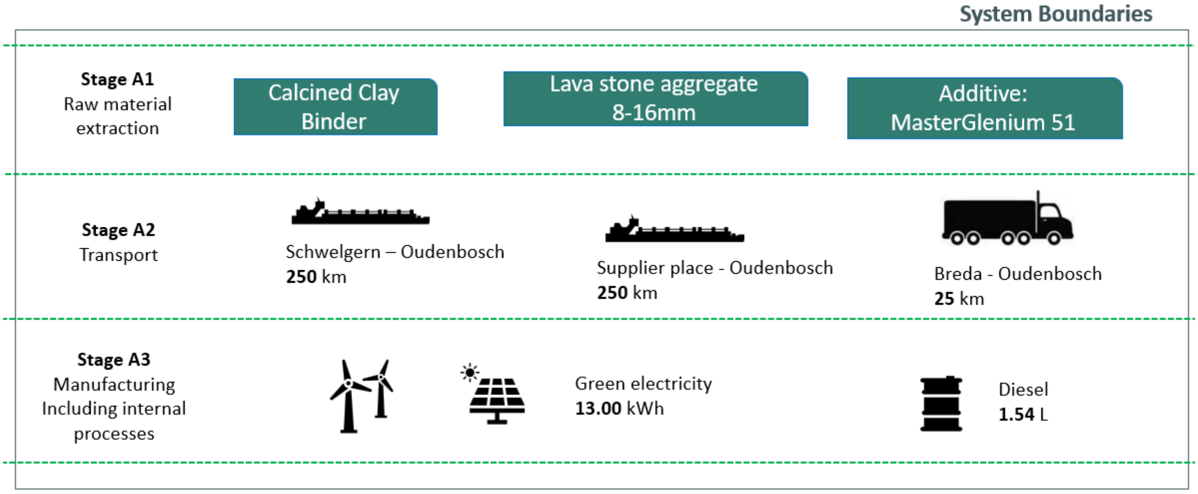


Figure 6.4: Process tree for C^3 binder with lava stone aggregates.

Elaboration on the process tree

Calcined Clay binder (C^3): The low carbon binder used for the mix is supplied by a company in Schwelgern in Germany and transported by an inland vessel to Oudenbosch at a distance of 250 km. Environmental data are retrieved from Ontwerptool Groen Beton v7 with environmental profiles:

1. C^3 binder: For the C^3 binder, no environmental profile could be found, only the final ECI value was provided based on the standard EN 15804+A1 (€ 20.46/ton)
2. Transportation: Transport, freight, inland waterways, barge RER | market for transport, freight, inland waterways, barge| Cut-off, U

Lava stone aggregate: Lava stone aggregate is sourced by a company situated 250 km from the Oudenbosch facility, and transportation is carried out by inland vessel. Environmental data for lava stone aggregate is retrieved from Ecoinvent and for transportation from Ontwerptool Groen Beton v7 with environmental profiles:

1. Lava stone aggregate: 0063-fab & Bims (puimsteen, vulkanisch gesteente, heklabims, liparibims, yalibims; o.b.v Pumice GLO| market for | Cut-off, U = inclusief 124 km transportmix) Overig transport toevoegen obv herkmost
2. Transportation: Transport, freight, inland waterways, barge RER | market for transport, freight, inland waterways, barge| Cut-off, U

Additive: The additive that is being used in the mix is supplied by a company in Breda, a common superplasticizer used for the production facility in Oudenbosch. The superplasticizer is being transported by truck at a distance of 25 km. Environmental data are retrieved from Ontwerptool Groen Beton v7 with environmental profiles:

1. Superplasticizer: Polycarboxylates, 40% active substance RER |market for polycarboxylates, 40% active substance |Cut-off
2. Transportation: Transport, freight, lorry, unspecified GLO |market group for transport, freight, lorry, unspecified |Cut-off, U.

Manufacturing stage of $1m^3$ of concrete product: During manufacturing of $1m^3$ of concrete product, green electricity consisting of solar energy, wind energy onshore and offshore along with diesel consumption is being used in the composition of 13.00 kWh and 1.54 L respectively. Environmental data are retrieved from Ontwerptool Groen Beton v7 with environmental profiles that were introduced for the reference mix design.

Total production waste is determined to be 1.2% and is accounted for in the calculations of the total environmental impact. This waste is deposited as sludge.

LCA results

For the calculation of the ECI value, the proportion of each material (in kg) per m^3 of concrete product is used, but this information, along with the detailed ECI breakdown across LCA stages (A1-A3), is not reported for confidentiality reasons.

The life cycle impact analysis for calcined clay with lava stone aggregates based on EN 15804+A1 standard is presented in Table 6.4 below.

Table 6.4: LCA of C^3 with lava stone aggregates.

Environmental category	**A1-A3**
Abiotic depletion potential, non-fossil	8.88E-05
Abiotic depletion potential, fossil	4.17E-02
Global warming potential	1.95E+00
Ozone layer depletion	1.81E-04
Photochemical formation	5.59E-02
Acidification	1.05E+00
Eutrophication	4.85E-01
Human toxicity	1.19E+00
Freshwater aquatic ecotoxicity potential	8.89E-03
Marine aquatic ecotoxicity potential	1.02E-01
Terrestrial ecotoxicity potential	5.16E-03
Total ECI	**€ 11.51**

It is important to note that at the A1 stage, no specific information is provided for the C^3 binder regarding the different environmental impact indicators; only the total ECI value is given.

Results and interpretation

Final ECI value based on EN 15804+A1 is calculated to be €11.51, with the most impactful stage being the raw material extraction stage, specifically the binder material. In the transportation stage, the aggregates result in the highest ECI due to their largest proportion and longest distance compared to the other half-products. Finally, in the manufacturing stage, diesel usage incurs the highest ECI value.

Regarding the environmental category most affected by the production of $1m^3$ of this concrete product, it is not ultimately clear as the ECI costs per environmental category of binder production are not provided. However, the same outcome as in the reference mix is expected. If the environmental outcomes for the binder are not taken into account, GWP accounts for the highest ECI value, followed by HTP and AP. Conclusions are drawn for CO_2 emissions since kg of CO_2 emitted per ton of C^3 binder are known. For the production of this concrete product, 151.6 kg of CO_2 are emitted, with the highest proportion attributed to binder production (stage A1).

6.2.3. LCA Calcined clay with recycled aggregates

Full product description

The mix developed with the low carbon calcined clay binder is being evaluated for its environmental performance. In the following Figure 6.4, the process tree for the mix of calcined clay with recycled concrete aggregate is presented, including the transportation method used for each half-product along with the energy used for the manufacturing phase.

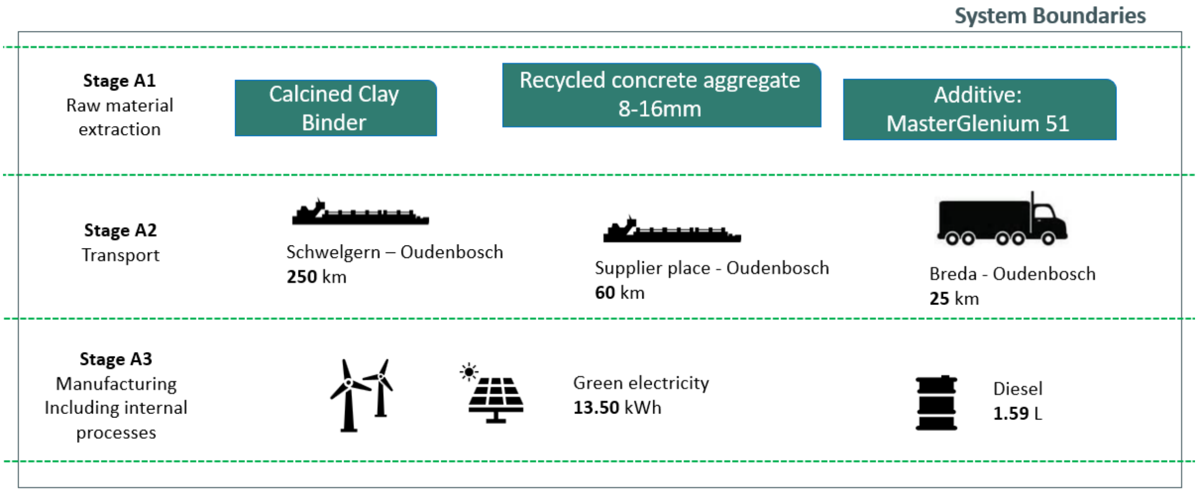


Figure 6.5: Process tree for C^3 binder with recycled concrete aggregates.

Elaboration on the process tree

Calcined Clay binder (C^3): The low carbon binder used for the mix is supplied by a company in Schwelgern in Germany and transported by an inland vessel to Oudenbosch at a distance of 250 km. Environmental data are retrieved from Ontwerptool Groen Beton v7 with environmental profiles:

1. C^3 binder: For the C^3 binder, no environmental profile could be found, only the final ECI value was provided based on the standard EN 15804+A1 (€ 20.46/ton)
2. Transportation: Transport, freight, inland waterways, barge RER | market for transport, freight, inland waterways, barge| Cut-off, U

Recycled concrete aggregate: Recycled concrete aggregate average distance is taken into account, which is 60 km away from the production site. The transportation is carried out by inland vessel. Environmental data are retrieved from Ontwerptool Groen Beton v7 with environmental profiles:

1. Recycled concrete aggregate: 0157-fab & Concrete granulate (= 0-values because 'free of environmental burden') - NMDv3.
2. Transportation: Transport, freight, inland waterways, barge RER | market for transport, freight, inland waterways, barge| Cut-off, U

Additive: The additive that is being used in the mix is supplied by a company in Breda, a common superplasticizer used for the production facility in Oudenbosch. The superplasticizer is being transported by truck at a distance of 25 km. Environmental data are retrieved from Ontwerptool Groen Beton v7 with environmental profiles:

1. Superplasticizer: Polycarboxylates, 40% active substance RER |market for polycarboxylates, 40% active substance |Cut-off
2. Transportation: Transport, freight, lorry, unspecified GLO |market group for transport, freight, lorry, unspecified |Cut-off, U.

Manufacturing stage of $1m^3$ of concrete product: During manufacturing of $1m^3$ of concrete product, green electricity consisting of solar energy, wind energy onshore and offshore along with diesel consumption is being used in the composition of 13.50 kWh and 1.59 L respectively. Environmental data are retrieved from Ontwerptool Groen Beton v7 with environmental profiles that were introduced for the reference mix design.

Total production waste is determined to be 1.2% and is accounted for in the calculations of the total environmental impact. This waste is deposited as sludge.

LCA results

For the calculation of the ECI value, the proportion of each material (in kg) per m^3 of concrete product is used, but this information, along with the detailed ECI breakdown across LCA stages (A1-A3), is not reported for confidentiality reasons.

The life cycle impact analysis for calcined clay with recycled concrete aggregates based on EN 15804+A1 standard is presented in Table 6.5 below.

Table 6.5: LCA of C^3 with recycled concrete aggregates.

Environmental category	**A1-A3**
Abiotic depletion potential, non-fossil	3.43E-05
Abiotic depletion potential, fossil	1.61E-02
Global warming potential	7.55E-01
Ozone layer depletion	6.99E-05
Photochemical formation	2.25E-02
Acidification	4.24E-01
Eutrophication	2.04E-01
Human toxicity	4.91E-01
Freshwater aquatic ecotoxicity potential	3.06E-03
Marine aquatic ecotoxicity potential	3.47E-02
Terrestrial ecotoxicity potential	3.21E-03
Total ECI	**€ 8.58**

It is important to note that at the A1 stage, no specific information is provided for the C^3 binder regarding the different environmental impact indicators; only the total ECI value is given.

Results and interpretation

Final ECI value based on EN 15804+A1 is calculated to be € 8.58, with the most impactful stage being the raw material extraction stage, specifically the binder material. In the transportation stage, the ECI values for binder and aggregate transportation are close, as the distance traveled for aggregates is reduced, resulting in a lower ECI value in the A2 stage. Finally, in the manufacturing stage, diesel usage incurs the highest ECI value.

Regarding the environmental category most affected by the production of $1m^3$ of this concrete product, it is not ultimately clear as the ECI costs per environmental category of binder production are not provided. However, the same outcome as in the reference mix is expected. If the environmental outcomes for the binder are not taken into account, GWP accounts for the highest ECI value, followed by HTP and AP. Conclusions are drawn for CO_2 emissions since kg of CO_2 emitted per ton of C^3 binder are known. For the production of this concrete product, 127.7 kg of CO_2 are emitted, with the highest proportion attributed to binder production (stage A1).

6.3. LCA comparison and conclusions

6.3.1. LCA comparison

After assessing the environmental performance of each concrete product, the resulting ECI values and CO_2 emissions are presented in Table 6.6.

Table 6.6: ECI and CO_2 comparisons of concrete products.

Mix design name	ECI value per m^3 concrete (€)	Reduction compared to reference	CO_2 emission per m^3 concrete in kg	Reduction compared to reference
Reference	19.78	-	286	-
C^3 - lava stone	11.51	-42%	152	-47%
C^3 - recycled concrete	8.58	-57%	128	-55%

According Table 6.6, reference mix has the highest ECI value as expected since it contains high carbon emission binder (OPC) along with limestone aggregates coming from a quarry in Belgium. Superplasticizer is used in all mix designs with the same proportion as in a typical percentage on concrete products. The mix with the C^3 binder and recycled aggregates results in the lowest ECI value, with a reduction on ECI almost 60%. This outcome is expected since recycled concrete aggregate used are zero burden and not negatively impact the final concrete product with extra fuel or electricity consumption. The production process of concrete aggregates is included in the disposal scenario of construction waste. At the same time, transportation of the recycled concrete aggregates was lowest compared with all other aggregates in the facility of Oudenbosch (60 km compared with 250 km of two other types of aggregates). A reduction in CO_2 emissions is also depicted as GWP is the primary environmental impact indicator affected by concrete production. The difference in CO_2 values reaches 55% reduction compared with the reference concrete product.

Following the mix with C^3 binder and lava stone aggregates results in a reduction of ECI value approximately in the percentage of 40% and in a reduction in the CO_2 emissions in the percentage of 50%. The main difference between the two concrete products - C^3-lava and C^3-recycled- is the aggregate selection. Lava stone aggregates are naturally made in nature through volcanic activity but should be crushed mechanically and sieved before the final use in the concrete product. Thus requirements of transportation from their place of formation, use of electricity and diesel is needed.

General outcomes for all mix designs studied are:

1. Raw material extraction stage (A1) holds the primary environmental burden in the production of the different concrete products with the most impactful product being the binder even if the low - carbon binder is used. However, use of C^3 binder can decrease the ECI value and CO_2 emission more than 50% as presented in Table 6.7 below.

Table 6.7: ECI and CO_2 comparisons of binder product.

Binder type	ECI value (€) per binder content	Reduction compared to OPC	CO_2 emission (kg/binder content in m^3)	Reduction compared to OPC
OPC	Confidential		Confidential	
C^3	Confidential	57%	Confidential	56%

2. In the transportation stage (A2), both the distance and the amount of materials that are transported play a significant role in affecting negatively the ECI value.
3. During the manufacturing phase (A3), the diesel consumption holds the highest ECI value in all different concrete products. It should be noted that if green electricity was not used the ECI value would be even higher.

6.3.2. LCA conclusions

To conclude, it is evident that both mix designs favor the sustainability performance of the concrete product. The environmental impact of concrete production has decreased by an average of 50% for both the ECI value and CO_2 emissions, which is significant. The best concrete product in terms of sustainability performance is the C^3 binder with recycled aggregates. Additionally, using recycled aggregates addresses the problem of managing the construction waste by recycling a by-product of the building sector into another type of construction, which further positively impacts this decision. However, the optimal mix design should not only have the best environmental performance but also meet bioreceptivity and mechanical performance requirements.

Factors that should also be considered when applying these results are:

- **Lifespan:** In a full LCA analysis, the use stage also holds an important role as it indicates the life expectancy of the different products. It is important to verify that the low-carbon concrete products can withstand the same construction purposes as the reference product for the same lifespan. If not, it means that more materials will be required to remake the same construction, potentially doubling the existing ECI value. Therefore, lifespan should be taken into account.
- **Recyclability:** Recyclability of a product is crucial, especially since the Netherlands has banned landfilling of concrete since 1997. Therefore, it is important to consider alternative methods from the 9R framework. In recent years, concrete waste in the Netherlands has been used in road applications. However, there was a significant concern about downcycling the concrete waste, as it was often mixed with other waste streams, such as brick fragments. This meant that its original purpose in the building sector was lost [85]. For that reason, new management methodologies are being considered to produce clean aggregates to be reintroduced into the building sector and new concrete products.

Since the proposed concrete products are made with already recycled concrete aggregates and lightweight aggregates with lower mechanical properties than natural aggregates, their incorporation in load-bearing constructions is deemed impossible. However, proper demolition and cleaning of bioreceptive walls/structures can make them recyclable in new constructions, such as those already used in non-load-bearing applications. Additionally, new recycling technologies like C2CA [174], which can remove a significant proportion of the cement paste from the aggregates to be reused back in their original purpose, show promise for the recycling of the proposed concrete products. The reuse of aggregates in the construction sector may not be possible after 2-3 End-of-Life cycles. Instead, they are expected to be used mostly as ground sand products rather than concrete aggregates.

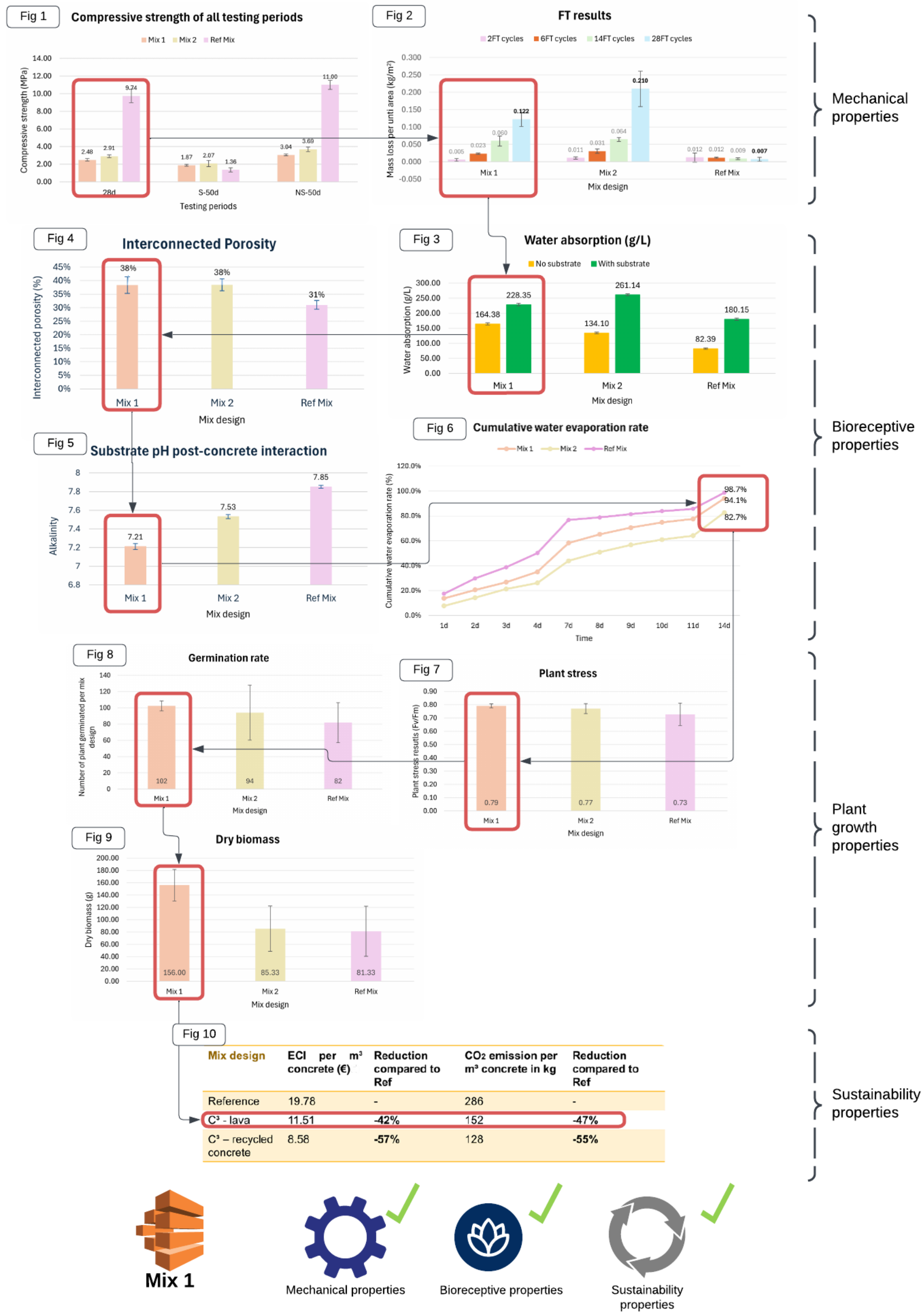
- **Utility:** The construction purposes of the proposed concrete products should also be considered. If the new concrete products cannot be applied in different uses like the reference one, this could diminish its use and its positive environmental impact may not be fully realized. Different usage purposes are important to consider, and stakeholder acceptance of the new concrete products for non-load-bearing construction purposes is crucial to take into account.
- **Market or costs:** In order to implement low-carbon concrete products, it is important that the raw materials for both the binder and aggregates are readily available and affordable. The abundance of clay reserves [109] makes it a promising substitute for clinker in the cement industry. It may take some time for alternative cement types to establish themselves in the market, but the results for C^3 look promising regarding technical availability, economic feasibility, low capital investment, and availability of raw materials, as introduced in Section 3.2.1. Additionally, recycled concrete aggregates are one of the biggest waste products in the Netherlands and are expected to increase further as some buildings reach their end of life in the coming years. In terms of material cost, the binder cost is the most significant, as it is a new type of binder, while both aggregates are already being used in the market and their feasibility has been proven. Preliminary studies for the C^3 binder have indicated that its cost may be lower than that of currently produced alternatives - lower than OPC materials and possibly lower for other SCM blends, depending on the local availability and price of these materials [175], [176], [85].
- **Biorecptivity performance:** Incorporating greenery into the wall structure can have several environmental benefits, including a positive impact on air and noise pollution, UHI, insulation properties, CO_2 sequestration, and human mental health as mentioned in Chapter 1. However, specific guidelines for incorporating these positive effects of greenery are currently lacking, but it is an important benefit that should be included in LCA assessment further decreasing the ECI value of the final concrete products [177].

6.4. LCA recommendations

Given that the binder is already substituted with a low-carbon binder, recommendations for the A1 stage of the LCA are not feasible. However, transportation plays an important role and has a significant impact on the calculated ECI values. Especially in the Netherlands, where freight transportation is feasible, opting for inland transportation of half-products is preferred since truck transportation results in higher ECI values. Additionally, substituting diesel lorries with electric or hydrogen lorries could further reduce the ECI burdens of transportation. The transportation distance is also crucial, suggesting that half-products should be delivered from companies within the Netherlands, and only if the materials are not available domestically should they be imported from other EU countries, preferably neighboring ones, to minimize the travelled distance. Regarding the manufacturing phase, the Oudenbosch facility already uses green electricity and does not rely entirely on diesel consumption, which positively affects the final ECI. However, fully supporting manufacturing with green electricity could further improve the ECI value. This would require investments and contracts with energy suppliers, involving different stakeholders to agree on meeting the energy requirements with 100% green electricity.

6.5. Optimal mix design

In this section, the identification of the optimal concrete mix design is discussed, taking into account the three design criteria: bioreceptivity, sustainability performance, and sufficient structural integrity in terms of compressive strength and freeze-thaw resistance. In Figure 6.6 below, the conclusion on the optimal mix design is presented.



Mix design	ECI per m³ concrete (€)	Reduction compared to Ref	CO₂ emission per m³ concrete in kg	Reduction compared to Ref
Reference	19.78	-	286	-
C³ - lava	11.51	**-42%**	152	**-47%**
C³ – recycled concrete	8.58	**-57%**	128	**-55%**

Figure 6.6: Identification of optimal mix design based on the three design criteria.

The mix design developed was studied based on three criteria: structural integrity (in terms of compressive strength and freeze-thaw (FT) resistance as a durability factor), bioreceptivity (linked with plant growth properties), and sustainability. Starting with the mechanical properties, compressive strength was evaluated after 28 days of curing, with 6 MPa identified in the literature as the minimum strength for non-load-bearing walls. The compressive strength of Mix 1 was evaluated to be close to 3 MPa. However, this value is not a limitation for the mix design, as construction alternatives (such as two-wall structures) are discussed in the literature for porous layer walls to enhance bioreceptivity (Chapter 1 in Section 1.2) . When compressive strength was calculated after drying with the growing substrate (S-50d - Fig. 1), the loss of compressive strength was lower than that of the reference mix, which showed the best results for compressive strength after 28 days. Regarding the durability factor of FT resistance, Mix 1 withstood 28 FT cycles with less scaled-off material compared to Mix 2 in all different FT cycles studied (Fig. 2). However, further validation of the FT durability is needed using different assessment methods, as the aggregates in Mix 1 and Mix 2 became loose when pressed by hand. This suggests the need for additional evaluation of FT durability by assessing compressive strength loss.

Regarding bioreceptive properties, Mix 1 performed better than Mix 2 and Ref mix in all properties studied. The interconnected porosity was calculated to be close to 38% (Fig. 4), and the substrate pH post-concrete interaction was found to be the lowest, with a value of 7.21 (Fig. 5). The water absorption of the concrete product was the highest due to the high porosity of the lava stone aggregates used (Fig. 3). As for water retention (Fig. 6), the results were affected by the substrate volume incorporated, as discussed in Section 5.3.4.

Regarding the plant growth results, Mix 1 demonstrated a higher average germination rate compared to the other mix designs, with consistent results across different samples, indicating robust bioreceptivity performance for this mix. However, Mix 2 showed a higher germination rate in one sample, suggesting the need for further validation of the germination results. Additionally, the quicker germination observed in Mix 1 led to longer root lengths and higher dry biomass compared to the other mix designs that germinated later. Plant growth results for all mix designs are discussed further in Chapter 7, Section 7.1.4.

In terms of sustainability performance, Mix 2 outperformed Mix 1 (see Fig. 10). However, Mix 1 achieved a 42% reduction in ECI and a 47% reduction in CO_2 emissions (for the production of 1 m^3 of concrete, considering A1-3 LCA stages) compared to the ref mix. This reduction is particularly significant when all design criteria and their results are considered holistically.

Taking everything into account, it is evident that Mix 1 meets all three design criteria studied and shows great potential for use in vertical greening systems. It demonstrates improved sustainability performance, good FT resistance in terms of mass loss, and a significant germination rate even in the first month.

However, this does not imply that Mix 2 is unsuitable for bioreceptive walls. Instead, it indicates that more testing is needed for plant growth results due to the high variance observed, which affects the robustness of the results. When evaluating other properties, the differences between the two mix designs are not significant, as factors such as porosity, substrate pH, and water absorption and retention are influenced by the growing substrate volume. In terms of sustainability performance, Mix 2 stands out, achieving nearly a 60% reduction in the ECI value and CO_2 emissions.

7

Discussion, conclusions and recommendations

This chapter concludes the research. Section 7.1 discusses the results in comparison to other literature findings and other notable outcomes of the thesis, followed by section 7.2, which presents the conclusions, and section 7.3, which contains recommendations for future research.

7.1. Discussion

In the discussion section, six different subsections are presented. The discussion starts with the added value of the methodology, followed by an analysis of how the research results relate to existing literature. It then addresses the freeze-thaw resistance property, sustainability, and bioreceptivity performance of the concrete. It concludes with the potential uses of the concrete products in vertical greening wall systems and the acceptance of the proposed mix design by stakeholders.

7.1.1. Added value of methodology

This research uses an iterative process to determine the volumetric composition and final design of the proposed bioreceptive and sustainable concrete product. This is recognized as the primary methodology for concluding the concrete mix designs. However, multi-criteria analysis (MCA) is a process that helps identify materials for their bioreceptiveness and sustainability, which adds extra value before the main methodology is applied. The added value of each process (MCA) and methodology (iterative process) is described separately.

Multi-criteria Analysis: Multi-criteria analysis is proven to be an important process for concluding the mix design and materials to be used in the concrete product. Given the variety of alternative binders and aggregates available on the market, multi-criteria analysis is an effective tool for identifying the most appropriate materials. It helps focus on the properties that both binder and aggregate should possess to be the best choices for a bioreceptive and sustainable mix design. Furthermore, properties identified during the multi-criteria analysis are validated by experimental tests, such as the water absorption capacity of lava stones and recycled aggregates compared to limestone aggregates, and the sustainability performance of C^3 binder compared to OPC.

In conclusion, multi-criteria analysis is a valuable process, as it uses literature review and an assessment system to focus on the appropriate materials for final testing, saving time on testing different alternatives.

Iterative process: The main methodology used in this research is the iterative process, which is employed to determine the binder and water content for the final concrete samples and, in general, the material proportions in the concrete product. Using this method, the volumetric composition of materials starts from a formulated hypothesis, and based on specific properties (compressive strength after 5 days of curing, the workability of the mix, and the observed interconnected porosity), new volumetric proportions are tested until the results align more closely with the expected outcomes. This method helps save materials and reduces the number of samples needed for testing, as no additional mortar samples are made once the properties are achieved. It also enables the quick determination of the volumetric proportion of binder, water, and aggregates, allowing for the efficient creation of the final concrete samples. Once the optimal volumetric proportion is determined, concrete samples are made and tested again for the three design criteria. The results are evaluated, and if optimization is needed, the process starts over, returning to the material selection process. In this way, delving into specific mix designs allows for easier comparison of properties and identification of necessary changes in material selection.

Overall, both methodologies complement each other well and are important for developing a mix design that meets the criteria of sustainability, bioreceptivity, and efficient structural integrity in terms of CS and FT. From the beginning of the process, the design criteria properties are taken into account, and each decision is driven by these requirements. Using these methodologies helps save a significant amount of material, as otherwise, numerous materials and products would need to be tested to finalize the mix design, prolonging the research process.

7.1.2. Relation of research results with literature

The relation of the research results with literature is difficult because, to the best of the author's knowledge, there is no research available that uses the same materials in the porous concrete product for wall structures as the ones studied in this thesis. Additionally, the porosity and aggregate gradation of the concrete and the properties being studied vary from one piece of literature to another. Furthermore, there is limited literature available on bioreceptive porous concrete wall structures, with most focusing on vegetation bioreceptive porous concrete. However, attempts are being made to find connections between the concrete mix designs and their applications in vertical greening.

Mechanical properties

Compressive strength: Concrete mix designs studied in the literature have shown low compressive strength results similar to those found in this research. Compressive strength varies depending on the materials used in the concrete product, along with factors such as porosity and aggregate gradation. Hemalatha, et al. [41] achieved a compressive strength of 4.5 MPa with a concrete mix design using OPC with a 20% addition of FA and natural aggregate up to 20 mm in size, with a design void ratio of 25%. Riley, et al. [6] attained the highest compressive strength result (10 MPa) using OPC with crushed limestone in the sizes of 6-10 mm and a void ratio of 30%. Jakubovskis, et al. [38] created a porous concrete product using OPC and different fractions of CEC aggregates, with the highest fraction being 8/16 mm and compressive strength reached 2.50 MPa. Meanwhile, Zhao, et al. [42] developed porous concrete using MPC with 20% GBFS, crushed stone ranging from 19 to 26.5 mm, with a porosity close to 30% and compressive strength reached 6.50 MPa.

Despite differences in mix designs, a similar trend is observed between the research and literature findings. Higher porosity leads to lower compressive strength results, which are closely affected by the binder type, aggregate type, and gradation. The highest compressive strength identified by Riley, et al. [6] with OPC and limestone aggregates sized 6-10 mm closely aligns with the research findings on the compressive strength of the reference mix using an OPC binder and limestone aggregates sized 8-16 mm.

In Figure 7.1 below, compressive strength results from research and literature findings for wall structures are depicted.

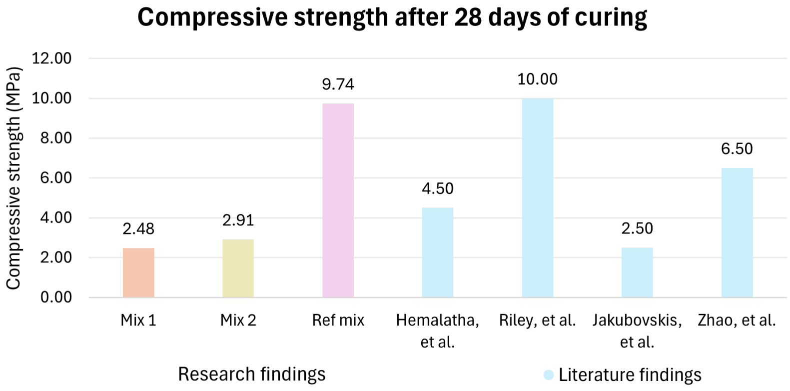


Figure 7.1: Compressive strength results of both literature and research.

According to Figure 7.1, only three mix designs meet the 6 MPa requirement for non-load bearing walls. However, the mix designs that fulfill this requirement are based on OPC binder and natural aggregates, which negatively impact the environmental performance of the final concrete product. Design ideas for low-strength concrete products are proposed in Section 7.1.6, where the concept of a two-layer structure is discussed.

Bioreceptive properties

Regarding bioreceptive properties, connections can be made mostly for porosity in bioreceptive concrete products for wall structures.

- *Porosity*

  Porosity is identified as a key factor for bioreceptive concrete, as it facilitates nutrient and water movement through the interconnected pores and provides space for root development. In most of the studies, when referring to porosity, the interconnected porosity is used and calculated by Equation 4.1. In Figure 7.2 below, the interconnected porosity of concrete products of both literature and research is presented.

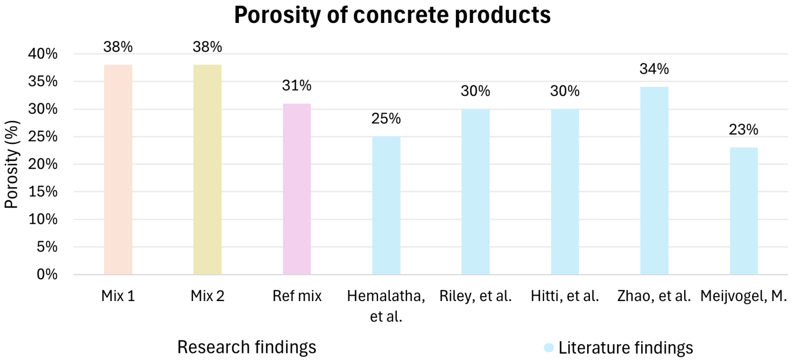


Figure 7.2: Interconnected porosity of concrete products of both literature and research.

  Interconnected porosity ranges between 23% and 34%, showcasing a specific design requirement when designing a bioreceptive porous concrete mix for wall structures. This range of porosity values is primarily influenced by the aggregate size and gradation used in the mix designs, as well as the volume of binder content.

- *Water absorption*

  For the water absorption results, comparisons can only be made with Mix 1, which has already been tested in the literature, with and without the growing substrate, by Meijvogel, M. [156]. For Mix 2, no literature findings are available as it has not yet been tested for its bioreceptivity performance. The results of water absorption for Mix 1 are presented in Table 7.1 below.

Table 7.1: Water absorption results of both literature and research.

	Water absorption (g/L)		
	Research findings	Literature findings	Source
Mix 1 (no substrate)	164.38	188.80	[156]
Mix 1 (with substrate)	228.35	220.60	[156]

  It is evident from Table 7.1 that the research findings agree with the literature when using lava stone aggregate in the size of 8/16 mm, combined with CEM III/B 42.5 N and admixture. Given that both mix designs are porous and the proportion of aggregate is high, water absorption can be correlated with the aggregate type. This correlation showcases the already verified result in the literature that lava stone aggregates are highly porous.

7.1.3. Freeze-thaw performance

Freeze-thaw resistance is an important factor tested for concrete products to evaluate their durability under varying weather conditions, especially in cold climates. When the temperature drops below zero, the water inside the concrete freezes and expands, exerting pressure on the remaining liquid water in the nearby capillaries and inducing stress [113]. If this stress exceeds the maximum tensile strength of the concrete, cracks begin to form, leading to deformation of the concrete product and deterioration of its properties [113].

Given that the proposed bioreceptive concrete mix is designed for vertical greening systems, the durability factor in terms of freeze-thaw resistance is a critical parameter to consider. This is particularly important due to the high porosity of the proposed product, which leads to higher water absorption, potentially resulting in greater deformation from cracking. Additionally, the low bonding force between the aggregate and the binder, owing to the low binder content and compressive strength, further influences the freeze-thaw resistance.

As a result, freeze-thaw resistance is assessed without the use of de-icing salts (such as NaCl), because this mix is intended for vertical greening systems. In these applications, contact with de-icing salts is limited or occurs at lower concentrations compared to horizontal surfaces like bridges or roads, where the combined effects of freeze-thaw cycles and chloride penetration are typically evaluated.

The results of freeze-thaw resistance for the concrete products studied showed that all mix designs withstood the 28 FT cycles. The mass loss, which was used as the failure criterion for assessment, was minimal. The reference mix had the lowest mass loss per unit area, equal to 0.007 kg/m^2, followed by Mix 1 with 0.122 kg/m^2, and Mix 2 with 0.210 kg/m^2. However, after the 28 FT cycles and the standard testing process, it was observed that the aggregates in Mix 1 and Mix 2 came loose from some samples when pressed by hand. This suggests that the compressive strength of these products may have decreased, and it is recommended to further test compressive strength after FT cycles.

This observation aligns with findings in the literature, where FT durability in porous concrete often shows minimal or no mass loss, yet the samples exhibit visible cracks and reduced load-bearing capacity [79]. Similar phenomena were observed in the samples for Mix 1 and Mix 2, where microcracks were visible on the surface after the 28FT cycles, and aggregates came loose but remained intact and unbroken. This indicates that the deterioration was concentrated in the interfacial transition zone (ITZ) between the aggregate and the binder, suggesting a low bonding force due to the lower binder content used.

Overall, the FT durability results are promising for all mix designs studied. However, further validation is recommended to further assess compressive strength loss due to the loosening of aggregates. Additional recommendations for FT resistance are presented in Section 7.3 that follows.

7.1.4. Sustainability performance

The term ”sustainability” is difficult to define due to the various terminologies used in the literature, and measuring the sustainability performance of a product or service is challenging given the different methodologies and terminology employed in research. This study focuses on strong sustainability, which prioritizes environmental performance over social and economic considerations. A framework is used to identify actions that promote strong sustainability (Figure 1.3). This framework was applied when selecting the materials for the multi-criteria analysis. For each material investigated (both binder and aggregates), different strong sustainability actions were considered to assess the relevance of the materials.

For the binder, the selection process emphasized reducing carbon emissions and identifying alternative binders that could decrease these emissions. This was coupled with the economic allocation phenomenon, which applies to specific binder supplementary products and introduces variability in the environmental performance of the product, particularly in relation to economic monopolies. For the aggregate selection, the production process was evaluated, focusing on oil and energy consumption, extraction processes, and limiting the use of quarrying. Preference was given to waste products that are currently underutilized in the industry and typically downcycled, with the economic allocation effect applied as a limiting factor for the by-products.

After selecting the materials based on the factors explained, the reduction in environmental footprint was verified using an LCA assessment. The chosen half-products (binder and aggregates) were compared using an ECI value, which focuses on the environmental impacts and burdens of a 1 m^3 concrete product by quantifying the environmental impact during the raw material extraction of the half-products, their transportation, and the final manufacturing of the concrete product in Oudenbosch. The quantification of the ECI value confirmed the expected outcome: Mix 2, with C^3 binder and recycled aggregates, had the lowest ECI, followed by Mix 1 with C^3 binder and lava stone, and the reference mix with OPC and limestone aggregates (ECI_{Mix2} < ECI_{Mix1} <ECI_{RefMix}, thus validating the selection process.

However, the sustainability performance is focused on the material level, addressing only a small part of the total production process, as it quantifies the environmental impact at the product level and not during the full use phase, maintenance, or disposal scenario. The decision to quantify only the LCA stages A1-A3 is because the mix design is evaluated for its mechanical, bioreceptive, and sustainable properties, rather than the full production of the wall structure. If a full LCA was conducted, additional parameters would need to be defined, such as the design of the wall structure (whether it is a one- or two-layer structure), the design and material selection for the second layer, the materials and number of connections, and the width of the structure. These factors would need to be considered to perform a comprehensive assessment, but the current evaluation focuses specifically on the mix design. Nonetheless, it is recommended that a full LCA be conducted in the future to fully understand the environmental impact of the product, taking all different assessment stages into account.

This means that conclusions made about mix designs performing well at the product level may change when the full LCA is considered, especially given the differing life expectancy or durability factors of the proposed products.

7.1.5. Bioreceptivity performance

Bioreceptivity performance includes properties such as alkalinity, porosity, water absorption and retention, along with plant growth results. Starting with the water absorption and retention results, it was found that these are influenced by the volume of substrate, which is affected by incorporation and drying losses. While the absorption and retention results with the growing substrate can provide some indicative values, they are subject to variability and do not accurately characterize a specific mix design. This variability occurs because the growing substrate is not incorporated into the pores of the concrete but rather remains on the surface, and its distribution is influenced by sample preparation and the interconnected porosity on the surface, which is not controlled. Additionally, the manual incorporation of the substrate further affects the accuracy and results in losses on the surface of the concrete samples. In addition, direct comparisons between the water absorption and retention of the samples used for germination cannot be made, as these properties were measured on different samples, not on those tested for plant growth. Given that the volume of substrate changes and impacts water retention and absorption properties, no definitive conclusions can be drawn regarding the plant growth results. This is because only speculation, rather than measurements of the water absorption and retention properties of the actual samples, can support these explanations.

Regarding plant growth results, there were significant variances between the samples, particularly for Mix 2 and the Ref mix, leading to inconclusive final outcomes. As previously explained, the plant growth results cannot be fully explained by the water absorption and retention properties, nor can they be directly linked to the pH of the substrate or its porosity. Regarding pH, only minor differences were observed between the pH levels of the growing substrate after 1 month of interaction with the concrete samples (Mix 1 = 7.21, Mix 2 = 7.53, and Ref Mix = 7.85). Literature indicates that plants can germinate in higher pH environments [34], [31], which cannot explain the observed variations in germination rate and biomass. Concerning porosity, the interconnected porosity of the samples was measured (Mix 1 and Mix 2 = 38% and Ref Mix = 31%). This interconnected porosity does not affect the incorporation of the growing substrate itself, as the substrate does not penetrate into the pores of the concrete but remains on its surface. Instead, the interconnected porosity on the surface of the samples may influence substrate adherence, with surface interconnections potentially aiding the substrate's attachment. However, porosity cannot be directly linked to the plant growth results or explain the differences observed between the various mix designs.

As a result, the plant growth outcomes cannot be fully explained by the bioreceptive properties studied, though possible explanations can be proposed. The quicker germination rate observed in Mix 1, along with the differing germination periods among samples of the same mix design, may be influenced by outdoor conditions such as humidity variations, temperature changes, or seed predation. The samples were positioned under tree leaves in different locations, which could have resulted in varying water exposure during rain or limited shading due to the tree canopy. Additionally, potential seed predation by animals could have affected the germination timing and rates. This is supported by the fact that, even within Mix 1, not all samples germinated at the same time, impacting the final results and variability. For Mix 2, which showed a higher germination rate in one sample, similar external factors could be a reason, but substrate volume variances also need to be considered. If one sample had a higher volume of growing substrate compared to others, it could lead to increased water absorption and retention, which are crucial for the initial germination period of the plant species.

However, a specific explanation cannot be provided based on the current experimental setup, as different outdoor conditions were not measured for each sample, and water absorption and retention results influenced by the substrate were also not recorded. This highlights the need to modify the experimental setup to make the results more robust and to better understand the plant growth outcomes. To improve the setup, it is recommended to conduct plant growth tests in both laboratory and outdoor settings. This approach would allow for an assessment of how environmental factors affect germination results, germination timing, and dry biomass. In a laboratory setting, all samples would receive the same moisture levels and temperature, enabling a direct correlation between plant growth outcomes and these controlled conditions. Additionally, moisture and temperature sensors should be used to monitor the degree of saturation and its variation with temperature both inside and outside the sample. Besides evaluating environmental conditions for germination, plant growth should be tested with a consistent binder and varying aggregates, and vice versa, to understand how different types of binders or aggregates affect plant growth. In the current setup, Mix 1 and Mix 2 used the same binder with different aggregates, but germination results cannot be solely attributed to the water absorption capacity of the lava stone aggregates due to the influence of outdoor factors. Thus, more attention should be given to minimizing outdoor influences to better isolate the impact of different properties. Improvements to the plant growth experimental setup are presented in Figure 7.3 below.

Conduct plant growth tests in both laboratory and outdoor settings to assess how environmental factors affect germination and biomass.

Use moisture and temperature sensors to measure and understand how humidity and temperature impact germination.

Test plant growth with consistent binders and varying aggregates, and vice versa, to comprehensively understand how each variant affects plant growth.

Figure 7.3: Improvement on experimental set-up for plant growth test.

Overall, the preliminary testing indicates that plant germination can occur in the mix designs studied, positively confirming the bioreceptive performance of these designs. However, improvements to the experimental setup are needed to fully understand the differences in plant growth results among the various mix designs and to address the high variability between samples within each mix design.

7.1.6. Potential uses & Stakeholders acceptance

- *Potential uses & Design ideas:* The concrete mix design developed is made for use in vertical greening wall systems in the city infrastructure as a bioreceptive material, colonized by vascular plant species. Given its low mechanical properties in terms of compressive strength, its use is restricted to non-load-bearing applications.
    - In the city envelope of the Netherlands, such an application is promising for bicycle walls used as soil supports in the bicycle infrastructure or underpasses when the compressive strength requirements are being covered. Because no specific mechanical requirements are given in the literature for underpass bicycle walls, it is tailored to the stakeholder's requirements when a new underpass wall is structured. When the compressive strength test results obtained for Mix 1 and 2 do not cover the mechanical strength requirements, a two-layer wall structure can be used as an alternative. In this case, the surface layer of the wall can be made from porous concrete and growing substrate can be applied to feature bioreceptivity and plant growth and a backing structure can be made to provide structural integrity. However, this alternative of the two structure wall requires further research in terms of the connections between the two layers and the design of the backing layer to increase the structural integrity but sustain the environmental performance of the final product made by both layers of the wall structure.
    - Another alternative for the mix design developed is noise barrier walls in highways in road infrastructures. Again stakeholder requirements should be taken into account regarding mechanical properties.

  Even if a porous concrete wall is made with no backing structure, the design of the wall dimensions and width are important to be determined through statics or numerical analysis.

  - When designing a self-porous layer or a two-layer structure, it is important to consider the irrigation system, as plants need watering during dry periods to avoid damage. Consequently, the design in both cases should incorporate an irrigation system, preferably a closed system that can reuse water or store rainwater for use during dry periods. Additionally, moisture sensors can be installed in a bioreceptive wall to monitor the humidity of the growing substrate. When the substrate is dry, the irrigation system can automatically provide the necessary water.

- *Stakeholders acceptance:*
  Technical acceptance: The new bioreceptive mix design proposed has not yet been evaluated by the industry. In this paragraph, the technical requirements for stakeholder acceptance are discussed.

  - Requirements such as structural integrity are discussed through compressive strength and freeze-thaw resistance in Section 6.5. Simultaneously, the proposed mix design is identified as a sustainable concrete product suitable for use in the city's envelope, with reductions in both ECI values and CO_2 emissions discussed further in Section 6.5. However, a promising material in the industry requires more than just structural integrity and sustainability performance.
  - An important requirement is the availability of the materials proposed for the mix, as previously discussed in the Multi-criteria analysis in Chapter 4 for both binder and aggregates. Availability is closely linked to the economic feasibility of widespread adoption. When materials are available in vast proportions, costs are also kept at a reasonable level and no economic problems are faced up in the concrete industry. This applies to both the binder and aggregates used in the designed concrete product.
  - Technical availability is another aspect to be considered, as C^3 binder is used. As already discussed in Chapter 4, the production of this binder can be done in a normal rotary kiln, and no additional investment costs are needed for a new production facility.
  - Another important factor to consider is how similar this product is to existing products in the concrete industry. The acceptance of stakeholders often depends on the product's familiarity and safety within the market. Because the C^3 binder is comparable to other cement that incorporate SCMs, it adds an extra level of security, making it easier to gradually integrate into the concrete industry. The aggregates used are already widely used in the Dutch industry. Overall, the final porous concrete product is not novel and should generally be accepted for use by the stakeholders if covers mechanical requirements.
  - An important aspect to consider is the economic cost, including installation and maintenance expenses. These costs will depend on the final design of the bioreceptive concrete wall, particularly if it is a two-layer structure. Further analysis is needed to estimate installation costs for each design variation. For maintenance costs, a pilot testing process can help address stakeholder concerns by providing data on performance and maintenance requirements.
  - Finally, ease of maintenance is another crucial factor. This includes understanding the frequency and type of maintenance required, as well as the level of expertise needed for upkeep.

  Willingless for stakeholders to invest: In addition to meeting technical requirements for market introduction, it is crucial to consider the willingness and interest of stakeholders, such as municipalities and investors, in accepting the bioreceptive mix design.

  - *Municipality willingness:* The municipality, as the primary governing body responsible for urban planning, infrastructure, housing, and environmental management in each city, plays a crucial role in the adoption and implementation of bioreceptive wall structures within the urban areas in the Netherlands. Considering the climate ambitions set forth by the EU for all member states [128], and the specific sustainability goals of Dutch municipalities [178], the integration of bioreceptive walls could enhance the living space and aesthetic appeal of urban areas. If the municipality's budget is not a limiting factor for the implementation of bioreceptive walls, the application could bring multiple benefits to the city's environment as documented in Chapter 1. This could be further assessed through questionnaires distributed to the residents to understand their perspective on bioreceptive walls in their cities, how they feel about them, and how they think their daily lives could be improved. Additionally, a small pilot test could be conducted in the city before final construction to familiarize residents with the concept of bioreceptive walls and to obtain visual feedback before distributing the questionnaires.

It is believed that residents would have a positive attitude towards such structures in the urban environment, as despite the benefits which cannot be easily quantified by residents (decrease UHI, air and noise pollution etc), the aesthetic appeal and the incorporation of greenery have been found to improve people's mental health [16], [18].

- *Investor willingness:* When a municipality establishes specific climate goals and supports the use of bioreceptive concrete walls, construction investors are more likely to align with these objectives and consider such projects. Additionally, BREEAM certification can further promote investment in bioreceptive wall projects within a city. BREEAM's strong recognition among developers and investors emphasizes its influence and relevance in the local market [179]. For investors, BREEAM certification signifies a commitment to sustainability, enhancing the attractiveness of projects and facilitating approval from construction stakeholders. It also offers potential economic benefits for investors based on the qualification outcome [179]. In conclusion, both the municipality's sustainability targets and the potential for a project to be certified by BREEAM are significant factors for an investor when considering an investment in projects such as bioreceptive wall structures.

7.2. Conclusions

In this thesis, concrete mix designs were developed to be both bioreceptive and sustainable while also meeting mechanical properties for structural integrity in terms of compressive strength and FT resistance. Three different mix designs were proposed: one reference mix using the most common materials in the concrete industry (OPC and limestone aggregates) and two alternatives where materials were selected after a multi-criteria analysis of binders and aggregates to meet the three design criteria mentioned. The alternative binder used, Calcined Clay, is a low-carbon emission binder known for its potential to replace OPC. Aggregates used were lava stone (Mix 1), known for their increased porosity, and recycled concrete aggregates (Mix 2), an important waste product of the building industry. Concrete samples were made and tested based on the three design criteria. The following conclusions could be obtained and key findings are indicated with the abbreviation KF.

Conclusions - Growing substrate incorporation

- **KF:** The study investigated porous concrete with the addition of a growing substrate. Different incorporation methods of the substrate were tested, addressing a gap in the existing literature. The results demonstrate that while the concrete samples achieve high porosity, the growing substrate does not penetrate the concrete's pores. Instead, it remains on the surface of the cubes.
- For all methods tested, water pouring is selected for its ease of execution and potential application in industrial settings.

Conclusions - Mechanical properties

- In terms of mechanical properties, the compressive strength (CS) -after 28 days of curing- for Mix 1 (2.5 MPa) and Mix 2 (3 MPa) did not meet the 6 MPa strength requirement for non-load-bearing walls as specified in the literature. However, strength requirements can vary depending on stakeholder needs.
- **KF:** Although the concrete products were highly porous and exhibited relatively low compressive strength, all samples demonstrated resilience in FT resistance when mass loss assessed. This makes them promising for use in the Netherlands' climate, particularly regarding durability in cold weather conditions and suggests great potential for vertical greening systems. Specifically, after 28 freeze-thaw cycles with tap water as the freezing medium, mass loss per unit area was calculated to be 0.007 kg/m^2 for Ref mix, 0.122 kg/m^2 for Mix 1 and 0.210 kg/m^2 for Mix 2 (Ref $_{28FT}$ > Mix 1 $_{28FT}$ > Mix 2 $_{28FT}$). It should be noted that after 28 FT cycles and standard testing, the aggregates in Mix 1 and Mix 2 became loose when pressed by hand, indicating a loss of compressive strength. This observation needs to be further evaluated and is discussed in the recommendations chapter.

Conclusions - Bioreceptive properties

- The use of lava stone and RCA, increases the porosity and water absorption performance of the concrete product.
- **KF:** The volume of the substrate incorporated in the concrete samples is variant, affecting the water absorption and retention results. Variations in the volume are due to the losses during the incorporation and drying process.

- Leaching of compounds from the concrete layer, leads to an increase of the pH of the growing substrate after 1 month of interaction of the substrate with the concrete samples with the highest increase on Ref mix, followed by Mix 2 and Mix 1 (Ref $_{pH}$ > Mix 2 $_{pH}$ > Mix 1 $_{pH}$).
- **KF:** Regarding plant growth results, all mix designs exhibited germination after one month. However, Mix 1 achieved the highest average germination rate, dry biomass, and fastest germination. In contrast, Mix 2 and the reference mix showed high variability in plant growth results across different samples, which may be related to outdoor germination conditions. Further validation is proposed, and a new experimental setup is recommended to achieve more robust plant growth results in the recommendation chapter.
- Measurements of Fv/Fm ratio showed that all plants germinated were not stressed and were within the range of 0.79-0.84, defined as the ratio for healthy and unstressed plants.

Conclusions - Sustainability properties

- Mix 1 and Mix 2 positively impact the environmental burden of the concrete product. They reduce both the ECI and CO_2 emissions by an average of 50% per 1m^3 of concrete, considering LCA stages A1-A3.
- The use of C^3 binder reduces the ECI and CO_2 emissions from the binder material extraction stage by 60% compared to OPC binder, further demonstrating that this binder is a low-carbon alternative.

Final Conclusion

- Mix designs tested for their bioreceptivity, sustainability and structural integrity in terms of CS and FT, show a great potential to be used in vertical greening systems.
- **KF:** Mix 1 with lava stone is concluded as the optimal concrete mix design based on all designed criteria studied, name structural integrity (compressive strength and FT resistance), sustainability and bioreceptivity performance.

7.3. Recommendations

This research answers some questions with regard of developing bioreceptive and sustainable porous concrete products for vertical greening systems in the city's infrastructure, but recommendations for future research remain. Key recommendations are indicated with the abbreviation KR.

Recommendations - Materials & Mix designs

Given the relatively low compressive strength of Mix 1 and Mix 2, along with the loosening of aggregates after 28 FT cycles and the failure occurring at the interfacial transition zone, the following recommendations are presented for the materials used in the mix designs.

- Recycled concrete aggregates and lava stone were used to fully substitute natural aggregates. However, natural aggregates can be reintroduced in varying proportions (20%, 40%, and 60% of the total aggregate content) to improve compressive strength, as supported by the literature. Although the breaking point of the reference mix was also identified at the interfacial transition zone, the reference samples did not experience complete fractures; instead, they exhibited smaller cracks. Therefore, substituting lightweight and recycled aggregates with a proportion of natural aggregates is expected to enhance the mechanical performance of the product, while increasing the ECI cost.
- The amount of binder used adequately covers the aggregates but is relatively small. It is recommended to test a higher proportion of binder, as the interfacial transition zone has been identified as the primary area of failure for both compressive strength and freeze-thaw resistance after 28 FT cycles for Mix 1 and 2. Increasing the binder content, could further ameliorate the bonding force between the aggregate and the binder, possibly leading to better mechanical properties in terms of compressive strength and FT resistance.
- In the proposed mix designs, fine aggregates were not included. However, the inclusion of fine aggregates smaller than 4 mm has been shown to improve both compressive strength and FT resistance in porous concrete products [180]. Therefore, it is recommended to test the addition of fine aggregates in varying proportions, while keeping the percentage low to avoid compromising porosity.
- For the last two recommendations, it is expected that porosity will decrease, but since the growing substrate is not incorporated into the product and remains on the surface, decreasing porosity does not negatively impact the bioreceptivity performance of the concrete product.

Recommendations - Mechanical properties

- Compressive strength
    - The compressive strength results of concrete samples are unexpectedly low compared to mortar samples. The compressive strength of the mortar samples after 5 days of curing was almost the same as that of the concrete samples after 28 days. Therefore, it is proposed to test the compressive strength of the concrete samples after 7 and 14 days of curing to observe the strength development between different curing times.
    - **KR:** Compressive strength (CS) was measured after drying both with and without the growing substrate. An increase in CS was observed when no substrate was added, while a decrease was found when the substrate was present. The greatest decrease was noted in the reference mix, where CS dropped by nearly 90% compared to its strength after 28 days of curing. The soil's insulating effect, combined with the reference mix's lower porosity, reduced capillary pressure and stiffening effect, likely caused microcrack propagation and CS loss in the ref mix. However, this result might be related to the sample preparation of the tested batch. Therefore, it is recommended to test a new batch under the same conditions. If the results are consistent, Scanning Electron Microscopy (SEM) could be used to validate microcrack propagation in the reference mix.
- Freeze-thaw resistance
    - **KR:** Regarding freeze-thaw resistance, only the concrete cubes were tested, not the final product incorporating the growing substrate. Since the water absorption capacity measured for each mix design was higher after substrate incorporation, it is expected that a proportion of water will be absorbed by the fine soil, reducing the free water inside the voids. This reduction in free water can help minimize the repeated hydrostatic pressure that can lead to damage or even destruction of the concrete product. This suggests that freeze-thaw resistance could be further enhanced when the growing substrate is incorporated into the concrete product. However, there is a concern that after several freeze-thaw cycles, the substrate might decrease in volume on the concrete sample. This hypothesis requires additional testing to confirm these assumptions.
    - **KR:** Although no deterioration of the concrete samples from Mix 1 and Mix 2 was observed after 28 freeze-thaw (FT) cycles during standard testing, the aggregates became loose when pressed by hand. This behavior is believed to be linked to a decrease in compressive strength (CS) after repeated FT cycles. Therefore, it is important to study compressive strength loss after various FT cycles to better understand the deterioration of the mix design, rather than relying solely on mass loss measurements, which, as supported by literature, may not be the most relevant assessment method for porous concrete products.
    - Since the concrete samples remained intact and did not break after 28 FT cycles during standard testing, it is recommended to extend the testing period until breakage or material loss aligns with specific stakeholder requirements. This is particularly relevant for the reference mix, which showed the lowest mass loss after 28 FT cycles and aggregates did not break when pressed by hand. Extending the FT testing time could provide valuable insights into whether the loosening of aggregates is also a concern for the reference mix, or if its bonding strength is superior due to its particle size distribution (PSD). The reference mix uses aggregate sizes up to 16 mm, while Mix 1 and Mix 2 incorporate aggregates up to 22.4 mm with the same binder content, that could have impacted further the loosening of the aggregates.
    - Finally, it is proposed to test freeze-thaw (FT) resistance with the addition of sodium chloride (NaCl) to evaluate its effects compared to water. Although the application is for a vertical wall system with only indirect exposure to de-icing salts (through leaching from nearby horizontal surfaces), understanding how NaCl impacts FT resistance is still valuable for the porous concrete products studied.
- Other durability factors
    - **KR:** Considering the incorporation of a soil-based growing substrate in the concrete sample, it is recommended to measure sulfate attack as a durability factor for chemical attack. Sulfates present in the soil can react with elements of the concrete, potentially leading to deterioration such as cracking or spalling of the concrete product. Due to different sulfate attack solutions, the solution included in the soil-based substrate in a higher proportion should be tested as part of primary research. In a later stage, different solutions (more or less aggressive) can be tested to determine general conclusions regarding this durability factor.

Recommendation - Bioreceptive properties

- **KR:** Given the variability in germination results among the different samples for each mix design, improvements in the experimental setup for plant growth tests are recommended to achieve more robust outcomes. First, conducting plant growth tests in both laboratory and outdoor settings is suggested to evaluate how environmental factors affect germination and biomass. Second, using moisture and temperature sensors is recommended to measure and understand the impact of humidity and temperature on germination in both indoor and outdoor conditions. Finally, testing plant growth with a consistent binder while varying aggregates, and vice versa, can help determine how each factor affects plant growth.
- **KR:** The plant growth test should be extended beyond one month, as this duration is considered inadequate. Despite successful germination, plants did not reach their full growth potential within this timeframe. Extending the germination period is interesting for examining how seasonal climate variations affect germination rates and considering the potential impact of extreme events such as heavy rain, which can repeatedly affect the substrate within the concrete product, resulting in a gradual diminution in its volume. The reduction in the amount of available substrate may have an impact on the growth of plants.
- The growing substrate is composed of finely sieved potting soil mixed with an organic binder to help glue the soil within the pores of the concrete product. While this substrate has shown promising performance, testing different ratios of soil-to-binder proportions could further validate the effectiveness of the current 10:1 ratio.

Recommendations - Sustainability properties (LCA)

- In the current LCA, the FU is not readily identified due to the variety of products studied. Durability considerations should be taken into account to compare various concrete products and assess their environmental performance. This holistic approach ensures that different products can be compared accurately under the same durability and lifetime span, and that the results of the LCA analysis are properly interpreted.
- **KR:** The environmental performance of the concrete product is the main focus of the LCA assessment in this study. It is recommended to carry out a full LCA that takes into account every stage of the life cycle, including the use stage, end-of-life scenarios, and disposal scenarios. A comprehensive assessment will enable an in-depth analysis of the environmental impact of the concrete product. If the durability of the designed concrete product is lower than that of the reference mix, necessitating early-stage construction substitution, the product may be deemed less environmentally friendly.
- Together with the LCA assessment, a cost analysis of the concrete product manufacturing process should be conducted. This should include the cost of the materials and transportation costs used in the concrete product. The cost analysis should also be expanded to include manufacturing, disposal, and maintenance expenses in the overall evaluation of the concrete product. Conducting a cost analysis is advised because it can be challenging to apply a new concrete type in the industry due to higher material, construction, and maintenance costs, even if the mix designs perform well in the studied properties,
- **KR:** Incorporating greenery into the wall structure can have several environmental benefits, including a positive impact on air and noise pollution, UHI, insulation properties, CO_2 sequestration, and human mental health as mentioned in Chapter 1. However, specific guidelines for incorporating these positive effects of greenery are currently lacking, but it is an important benefit that should be included in the LCA assessment further decreasing the ECI value of the final concrete product.

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A

Additional data on experimental set-up

This appendix serves as an additional chapter describing the experimental setup used to define the aggregate properties and mechanical properties of the concrete samples according to EU standards. Additionally, it presents the procedures for making mortar samples and concrete samples for complementary purposes. It is noted that the mortar sample-making procedure differs from the standard mortar-making procedure defined by the EU.

A.1. Basic aggregate properties

A.1.1. Aggregate particle size distribution

Relevance: PSD is used to determine the different aggregate fractions and their proportions in the concrete mix. It is an important property to measure as it influences the particle composition within the concrete mix.

The used method: The PSD is performed based on NEN-EN 933-1:2012 (E).

Test set-up figure: Figure A.1 presents the test set up for obtaining the PSD of each aggregate type and the process is presented below.

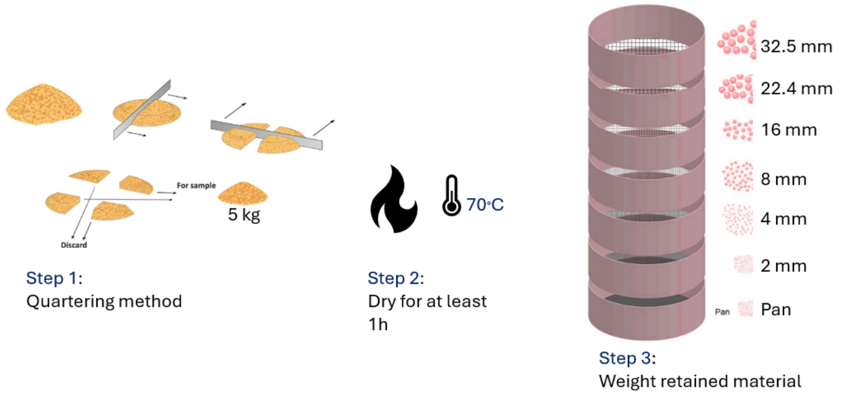

Figure A.1: Test set-up for PSD of aggregates.

Process: The process of PSD is described in the following steps:

1. A representative mix of aggregates is made after the quartering method until the mass of the specimen for the PSD test is 5 kg. The aggregates are then dried for at least 1 h before sieving.
2. The sieves are stuck from the smallest (0mm, pan) to the largest (32.5mm) and the specimen is put in the highest sieve.

3. Vibration occurs and the retained material in each sieve is weighted.
4. A table is made with the mass retained and cumulative percentage passed.
5. The PSD is made for each aggregate type sieved.
6. Results and conclusions are presented.

A.1.2. Aggregate water absorption and particle density

Relevance: Water absorption in an important properly as it affects the water content that needs to be added in the concrete mix in order to succeed the right workability of the mix and it affects compressive strength and durability of the concrete mix. Particle density is also mportant as it influences the mix proportions and volume of aggregates in a concrete mix. Knowing particle density also allows for efficient use of materials and decrease of waste in the concrete product.

The used method: Both experiments are performed based on NEN-EN 1097-6:2022 (E).

To obtain water absorption and particle density, two different processes are used. An important step in both tests is specimen sieving. Aggregates smaller than 8 mm are not used in the tests, as the aggregate size for the concrete samples is 8-16 mm, with sizes larger than 16 mm not removed. The upper aggregate size is 22.4 mm, and according to Table 2 in NEN-EN 1097-6:2022 (E), the minimum mass of the test portion for assessing these properties is interpolated to be 3.2 kg

Process - water absorption: The water absorption process is described in the following steps:

1. The proportion of 3.2 kg of aggregate specimen is weighted.
2. Aggregates are immersed in the water for 24 h.
3. Cloth is used to dry the surface of aggregates and their saturated mass is weighted (M_w).
4. Aggregates are placed in the oven for 24 h at 105°C.
5. Aggregate are left to cool and their dry mass is weighted (M_d).
6. Water absorption is determined by Equation A.1:

$$\text{WA} = \left(\frac{M_w - M_d}{M_d}\right) \times 100 \tag{A.1}$$

Test set-up figure: Figure A.2 presents the test set up for assessing the water absorption of each aggregate type.

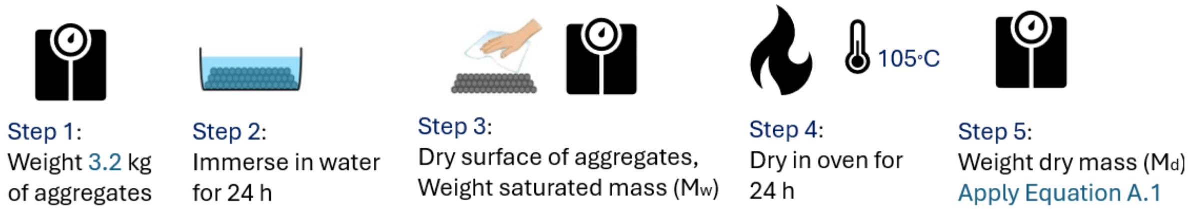

Figure A.2: Test set-up for water absorption of aggregates.

Process - particle density: The particle density process is described in the following steps:

1. A proportion of 3.2 kg of the aggregate specimen is weighed and dried in the oven for 24 hours at 105°C.
2. Aggregates are left to cool before the test.
3. The pycnometer is weighed (W_p), filled with water, and weighed again (W_{p+w}).
4. The volume of water in the pycnometer (V_1) is found using Equation A.2.

$$V_1 = \left(\frac{W_{p+w} - W_p}{p_w}\right) \times 100 \tag{A.2}$$

5. A certain weight of aggregates (W_a) is added to the pycnometer.

6. The pycnometer and aggregates are weighed (W_{p+a}).
7. Water is added to cover the aggregates, then the pycnometer is shaken to remove air bubbles, and more water is added to fill the pyknometer.
8. The weight of the pycnometer, water, and aggregates is found (W_{p+a+w}).
9. The volume of water in this case (V_2) is found using Equation A.3.

$$V_2 = \left(\frac{W_{p+a+w} - W_{p+a}}{p_w}\right) \times 100 \tag{A.3}$$

10. The volume of the aggregates (V_a) is found by subtracting V_1 from V_2.
11. The particle density is found by dividing the weight of the aggregates (W_a) by the volume they occupy in the pycnometer (V_a).

A.2. Concrete sample making

A.2.1. Mortar sample

Introduction: Concrete mortars are used to determine the correct binder content and water-to-binder ratio for making the final concrete samples. The selection process for binder content and water-to-binder ratio is described in Chapter 3, along with the conclusions on the final ratios chosen. This section introduces the process of making mortar samples.

Method: Given that the concrete type under study is porous, using sand would not result in comparable workability, compressive strength, and porosity outcomes in the concrete mix designs. Therefore, it is decided to use the aggregates under study for making the mortars, differing from the specifications in EN 196-1:2016 (E). Concrete mortars with dimensions 40 mm x 40 mm x 160 mm are produced. The preparation process also differs from the standard procedure in EU standard due to the large size of the aggregates, which could potentially damage a small Hobart mixer. Consequently, the mixing is performed manually.

Process: The process is described in the following steps:

1. The materials for the concrete mortars are weighed.
2. The aggregates and binder are mixed.
3. Water is added slowly, and the workability of the mix is checked.
4. Prism moulds with dimensions of 40 mm x 40 mm x 160 mm are filled with the concrete mix and covered with plastic foil for 1 day.
5. The concrete mortars are demoulded, and the samples are cured for 5 days before performing the compressive strength test.

A.2.2. Concrete sample

Method: For the concrete samples, cubes with dimensions 150 mm x 150 mm x 150 mm are produced based on EN 12390-1:2021 (E).

Process: The process is described in the following steps:

1. The materials for the concrete samples are weighted.
2. The aggregates and binder are mixed in the Hobart mixer of 40 L.
3. Water is added slowly, and the workability of the mix is checked.
4. Cube wooden moulds with dimensions 150 mm x 150 mm x 150 mm are filled with the concrete mix and covered with plastic foil for 1 day as presented in Figure A.3.
5. The concrete samples are demoulded, and the samples are cured for 28 days before the mechanical, bioreceptive and plant growth tests are performed.

A.2.3. Representation of sample making

The sample making for both mortar and concrete sample is presented in Figure A.3 below.

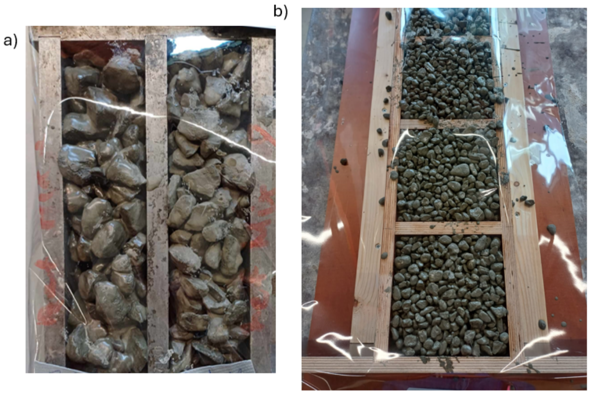

Figure A.3: Concrete sample making of a) mortars and b) cubes.

A.3. Mechanical properties

A.3.1. Compressive strength for mortar samples

Relevance: Compressive strength of mortar samples is tested to conclude on the binder content and water to binder ratio to be used in the final concrete samples.

Method: The compressive strength of mortar samples is performed based on EN 1015-11:2019 (E). The used dimensions for performing the compressive strength of mortar samples are 80x40x40mm as flexural strength breaks the sample into two halves. The tested area is 40x40mm.

Process: The process is described in the following steps:

1. After 5 days of curing, the samples are removed from the curing room. The test should be performed within 10 hours, and the samples should be stored in an environment with a temperature between 15-25°C.
2. The sample is placed in the compressive strength machine, and the flexural strength test is performed, splitting the sample into two halves.
3. For each half of the mortar, a compressive strength test is performed.
4. The loading rate used is 0.05 kN per second, and the start load is 0.1 kN.
5. The failure load in kN is recorded.
6. The compressive strength is determined by dividing the failure load (kN) by the area exposed to the load (40 x 40 mm).
7. Results are interpreted and discussed.

Test set-up figure: Figure A.4 presents the test set up used for compressive strength of mortar samples.

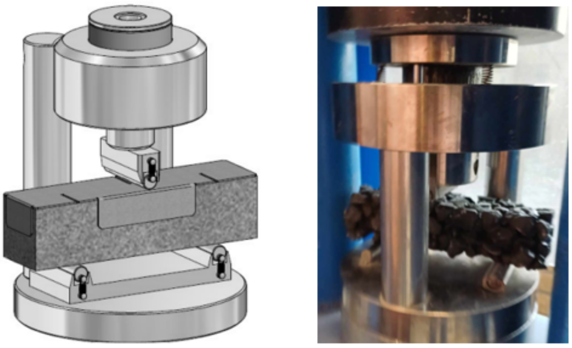

Figure A.4: Test set-up for compressive strength of mortar samples.

A.3.2. Compressive strength for concrete samples

Relevance: Compressive strength is tested as it is the most important property to characterize a concrete product, evaluating the proposed mix design in terms of structural integrity. Compressive strength is determined after 28-days of curing. The limitation for the porous concrete mix design is 6 Mpa for non-load-bearing structures [168] .

Method: The compressive strength of concrete samples is performed based on NEN-EN 12390-3:2019 (E).

Process: The process is described in the following steps:

1. After 28 days of curing, the samples are removed from the curing room. The test should be performed within 10 hours, and the samples should be stored in an environment with a temperature between 15-25°C.
2. Sample is placed in the compressive strength test machine.
3. The loading rate used is 13.5 kN per second.
4. The failure load in kN is recorded and the failure pattern is observed.
5. The compressive strength is determined by dividing the failure load (kN) by the area exposed to the load (150 mm x 150 mm).
6. Results are interpreted and discussed.

Test set-up figure: Figure A.5 below, presents the test set up for assessing compressive strength of concrete samples.

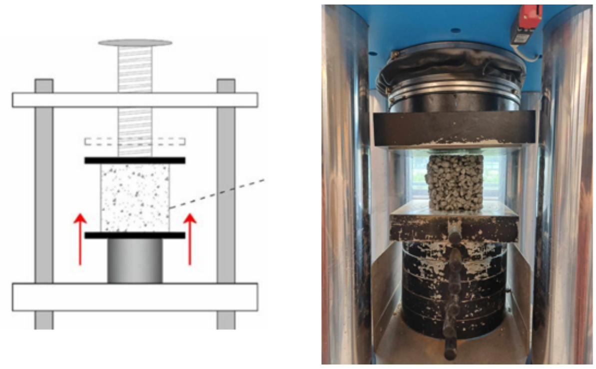

Figure A.5: Test set-up for compressive strength of cube samples.

A.3.3. Freeze-thaw resistance

Relevance: Freeze-thaw resistance is tested to determine if the freezing and thawing cycles negatively affect the concrete mix proposed. Especially in the Netherlands, where temperatures in the winter are below 0, and freezing and thawing cycles occur is important to check the durability of the mix design due to weather changes, along with its performance after different FT cycles (2, 6, 14 and 28 FT cycles).

Method: The freeze-thaw resistance is performed based on NEN-EN 12390-9:2016 (E), CDF test with no de-icing salts.

Process: The FT resistance test starts after 28 days of curing of the concrete samples. The 150 mm cube should be split in half and the specimens with sizes 150 mm x 150 mm x 75 mm are used for the FT test. The following steps are followed:

1. After 28 days of curing, the samples should be wrapped with butyl tape to insulate the sides of the cubes.
2. The samples are placed with the tested surface downwards inside a platform submerged in water to a height of 10 mm. They remain submerged for 7 days before the start of the freeze-thaw (FT) experiment and are monitored daily.
3. When the submersion period is finished, the specimens are placed in the FT machine with the testing surface facing downwards.

4. The FT cycle exposes each concrete sample in the cooling bath to temperatures ranging from -20±0.5°C (minimum temperature) to +20±1°C (maximum temperature).
5. After 2, 6, 14, and 28 FT cycles, the scaled material is collected by brushing it off the concrete and exposing it to ultrasonic vibration for almost 3 minutes. The loose material is dried at 105^{o}C for at least 24 hours and its mass is determined. At the same time, scaling assessment is conducted to check for cracks in the concrete.
6. The mass loss per unit area is determined.
7. Results are interpreted and discussed.

Test set-up figure: Figure A.6 below, presents the test set up for assessing freeze-thaw resistance of concrete samples.

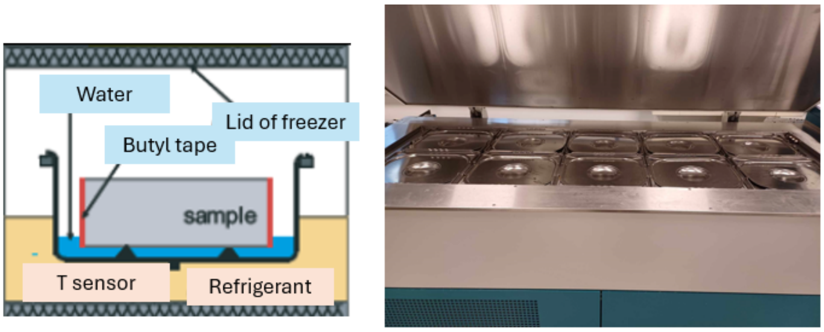

Figure A.6: Test set-up for freeze thaw resistance of cube samples.