Carbon Neutral Breakwater

An Integrated Approach to Identify Sustainable Materials, and Strategies to achieve a Carbon Neutral Breakwater Design

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Thesis report

by

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Preface

This thesis, "Carbon Neutral Breakwater: An Integrated Approach to Identify Sustainable Materials and Strategies to Achieve a Carbon-Neutral Breakwater Design," represents the completion of my academic journey at Delft University of Technology. My fascination with sustainable engineering solutions and my passion for environmental preservation have driven me to explore methods to mitigate the impacts of climate change on coastal infrastructure.

This research is carried out in collaboration with Witteveen+Bos, for which I am grateful. Furthermore, I am deeply grateful to my thesis supervisor, Prof. Dr. Ir. M.R.A. van Gent, for his expertise and encouragement were helpful in shaping the direction of my research. I would also like to extend my heartfelt thanks to my co-supervisors, Dr. Ing. M.Z. Voorendt and Ing. C. Kuiper, for their invaluable guidance throughout this project and for their insightful feedback and constant support. Special thanks to Ing. K. Jerez Nova from Witteveen+Bos for his external perspectives that enriched this study.

This research was made possible through the invaluable contributions of numerous individuals and organizations. I am deeply grateful to the experts who shared their extensive knowledge and insights on sustainable materials and construction practices, providing a solid foundation for the study. Their expertise was crucial in understanding the complexities and potential of various low-carbon technologies and materials. Additionally, I would like to express my gratitude to the companies that generously provided data and access to their projects, offering real-world examples that enriched the analysis. The collective efforts and support from these contributors have been helpful in advancing this research and paving the way for future developments in the field.

Undertaking this research has been a profoundly educational and rewarding experience. It has allowed me to develop new skills, overcome various challenges, and contribute to the field of sustainable engineering. I hope this work inspires further research and development in creating carbon neutral coastal protection solutions.

Tom Houben
Delft, August 2024

Summary

The research, "An Integrated Approach to Identify Sustainable Materials and Strategies to Achieve a Carbon-Neutral Breakwater Design," aims to design breakwaters that maintain structural integrity and functional performance while minimizing environmental impact. The research addresses the urgent need to reduce carbon emissions in coastal engineering, aligning with global climate change mitigation goals. The primary objective is to develop a comprehensive framework for designing carbon-neutral breakwaters.

The research starts with a comprehensive literature review on carbon emissions from breakwater construction, focusing on materials, construction activities, and life-cycle assessments (LCAs). This establishes a framework for understanding the carbon footprint at each construction stage. It then evaluates conventional and alternative construction equipment, analyzing different fuels and their impact on carbon emissions. Future prospects highlight potential advancements and innovations in construction practices and technologies. Additionally, a detailed inventory of conventional and innovative materials is created, assessing their carbon emissions, stability, and robustness for breakwater construction.

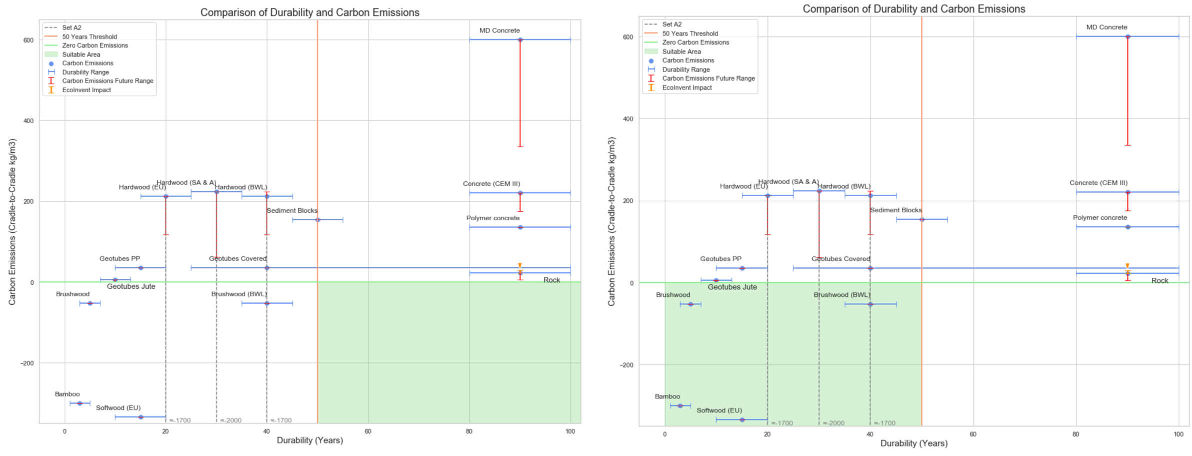
The research describes a systematic approach to evaluate materials and design concepts based on various criteria, including carbon emissions, structural requirements, and environmental impact. This methodology aims to identify the most suitable breakwater concept given specific boundary conditions. The approach includes an iterative pattern where the choice of carbon neutrality is set either as a requirement or as an evaluation criterion. This iterative process provides valuable insights into the challenges and bottlenecks of designing carbon-neutral breakwaters. The different steps involve:

- **System Analysis:** assessing the local environmental conditions, including wind data, hydraulic conditions, and subsoil data.
- **Defining Requirements and Criteria:** establishing the specific requirements for the breakwater design based on the local conditions and project goals, followed by the establishment of the evaluation criteria.
- **Verification of Design Concepts:** verifying the different breakwater design concepts based on the requirements, such as carbon emissions, functional requirements, durability, strength and suitability for the local conditions.
- **Evaluation and Selection:** using a multi-criteria analysis to score and rank the design alternatives based on the defined criteria, leading to the selection of the most suitable breakwater design.

The methodology is then verified with a case study on a breakwater in the Braassemermeer, following these steps. The research identifies the conventional rubble mound breakwater as the most suitable option for the Braassemermeer case study. This selection is based on a balanced consideration of structural integrity and environmental impact, demonstrating the practical application of the developed methodology for future breakwater designs.

The research highlights the need for an integrated approach, considering technical, environmental, and operational factors to enhance sustainability in breakwater projects. Figure 1a illustrates the search area for materials that are both carbon neutral or negative and have a lifespan of over 50 years. However, no material meets both criteria, necessitating a compromise between a small carbon footprint (using rock) or reduced structural lifespan. Figure 1b shows the green area for designing a carbon neutral breakwater without the lifespan requirement for materials, resulting in potential materials.

Brushwood grids, softwood, and bamboo present a promising alternative to traditional materials like concrete and rock for reducing carbon emissions. These materials are renewable and have lower energy requirements for production, with brushwood grids and bamboo also offering significant carbon sequestration capacities. However, challenges remain regarding their durability, with lifespans of up to 40 years when submerged, and their stability in high-energy marine environments due to wear and tear from constant wave action.In contrast, rock proves to be a viable option due to its relatively low carbon emissions, only 6 $kgCO_2/m^3$ if transported emission-free, and its ability to meet both stability and durability requirements in many applications.



(a) **(b)**

Figure 1: The search area under certain conditions

Furthermore, this study once again emphasizes that cement's energy-intensive production significantly contributes to carbon emissions. Alternatives like geopolymer concrete, which utilize industrial by-products like fly ash, show promise but are limited by their reliance on cement and the availability of by-products. Materials that require cement cannot achieve a carbon footprint below 100 kg_2/m^3, making them unsuitable for carbon neutrality goals. Geotextile tubes, with a low carbon footprint of just 35 kg CO_2/m^3, offer flexibility and ease of installation but require further research for marine applications. However, plastic alternatives like polypropylene are discouraged due to the risk of microplastic release.

Evaluations of DuboCalc and SimaPro show that while DuboCalc is user-friendly, its outdated data and process-focused approach limit its accuracy for current sustainability assessments in Dutch hydraulic engineering. SimaPro provides detailed life-cycle assessments and comprehensive environmental impact insights but requires significant expertise and time to use effectively. Both tools overlook the carbon sequestration capacity of materials, leading to overestimated carbon footprints. Consequently, companies often develop their own methods, adjusting data from EcoInvent and NMD to better meet their specific needs.

The transition to sustainable construction practices shows potential in electric and hydrogen-powered construction equipment. The carbon emissions on-site can already be completely brought down to zero for smaller projects with a limited amount of construction equipment. Expanding this to larger projects includes challenges like unfamiliarity of the use of new carbon neutral equipment, strict storage regulations of large amount of hydrogen and the high initial costs of material and infrastructure.

The integration of sustainable materials, innovative design methodologies, and advanced carbon quantification tools like SimaPro is crucial for reducing the overall carbon footprint of breakwaters. The validation through case studies, such as the implementation of brushwood grids in a coastal protection project, emphasizes the need for ongoing research, real-world testing, and the development of comprehensive life-cycle assessments to optimize the sustainability of breakwater projects. This integrated approach not only mitigates the immediate environmental impacts of construction but also aligns with global efforts to combat climate change and promote sustainable development.

Currently, building a carbon-neutral breakwater is not feasible unless adjustments are made to certain requirements, such as lifespan and transportation. No single material meets all environmental and durability criteria simultaneously, indicating the trade-offs between using low-carbon materials and ensuring the long-term durability and stability of breakwaters. The study concludes that integrating low-carbon materials, innovative design approaches, and sustainable transportation methods can substantially reduce the carbon footprint of breakwater construction. However, achieving carbon neutrality is a complex challenge that requires balancing environmental impact with functional performance and durability. Likewise, prescription by client to create requirement for carbon neutral equipment, would enhance the transition to carbon neutral construction material. Future research should focus on improving the long-term performance of sustainable materials, exploring alternative fuels, and developing more advanced life-cycle assessment tools to support sustainable construction practices.

Contents

Nomenclature

Abbreviations

Abbreviation	**Definition**
AQD	Armour stone Quality Designation
BEV	Battery electric vehicles
BWL	Below Water Level
CF	Carbon Footprint
DWT	Deadweight tonnage
EC	Embodied Carbon
ECI	Environmental Cost Indication
EoL	End-of-Life
EU	Europe
FCEV	Fuel cell electric vehicles
GHG	Greenhouse Gas
HDPE	High-density polyethylene
HFO	Heavy fuel oil
HGV	Heavy goods vehicle
HVO	Heavy vegetable oil
LCA	Life Cycle Assessment
LCB	Low-crested Breakwater
LFO	Liquefied fuel oil
LNG	Liquefied natural gas
MCA	Multi-criteria Analysis
MD	MagnaDense
md	Machine Day
MDE	Micro-Deval
MGO	Marine Gas Oil
NMD	Dutch Environmental Database
OPC	Ordinary portland cement
PP	Polypropylene
RCA	Recycled Concrete Aggregates
RE	Renewable Energy
RI	Random Consistency Index
RM	Rubble Mound
SA	South-America
SFS	Steel furnace slag
WNW	West Northwest
WTW	Well-to-wake

Symbols

Symbol	Definition	Unit
H_s	Significant Wave Height	[m]
h	Water Depth	[m]
M	Mass	[kg]
H_t	Transmitted Wave Height	[m]
T_p	Peak wave period	[s]
T_m	Mean wave period	[s]

1
Introduction

1.1. Thesis Motivation

Climate Change
World wide sustainability goals are set to cope with the current climate change. The increased exploitation of finite resources and combustion of fossil fuels enhance the global warming. It is predicted that the increase in global average temperature could exceed the threshold of 1.5 degrees by 2030 (Smith et al., 2018). Carbon dioxide (CO_2) is one of the largest contributors (Jones et al., 2023). In 2015, the Paris Climate Agreement was established which involved many countries that established low carbon emission policies. The European Union set a target of reaching a carbon-neutral EU by 2050 (European Union, 2020). This report explores the carbon emissions related to the construction of breakwaters nowadays and indicates the potential areas of improvement.

Relevance of this Research
In response to the increasing challenges presented by climate change, as outlined by the Paris Climate Agreement and EU policies, coastal engineering practices are undergoing a significant transformation. Dating back to 2000 B.C., the ancient Egyptians constructed a breakwater in Alexandria to safeguard their harbours. This application continued into the time of the Roman Empire, who made some significant development in the coastal engineering (Takahashi, 2002). Over the span of centuries, the main purpose of protecting harbours by breaking the waves, has remained constant. However, nowadays, breakwaters have become part of comprehensive coastal management strategies that also focus on sustainability and ecological values.

Contemporary breakwaters play various but crucial roles within safeguarding the coastlines. Not only do they protect the harbours from the incoming waves, but by reducing the wave height, they are able to mitigate the wave-induced sediment transport phenomena. By partially preventing both the cross-shore and long-shore transport, beach erosion can be reduced. Other functions of breakwaters include, the guiding of currents to ease the entrance for the vessels, preventing the siltation of the channel and providing quay facilities (Van den Bos and Verhagen, 2018). Yet, climate change emphasizes the importance of breakwaters and will affect the boundary conditions. Extreme weather conditions are more likely to occur due to the changing climate worldwide (Hoeppe, 2016).

1.2. Problem Analysis

1.2.1. Addressing the Findings of Previous Research

The need to transition towards carbon-neutral practices in the construction of breakwaters is both urgent and challenging. Large improvements have already been made towards eco-friendly constructions for locations with (mainly) lower hydraulic loads, by reducing the amount of material through optimizing the design and using recyclable elements. However, reaching carbon neutrality requires further research and tackling the existing challenges.

Concrete, steel and rock are three of the most commonly used materials in hydraulic constructions. They are associated with high levels of embodied carbon. Studies, conducted by Broekens et al. (2011), detail the carbon implications of these materials. For instance, the embodied carbon of typical materials used for breakwater construction like armour rock and quarry run can vary significantly. This study shows values of embodied carbon up to 93 $kgCO_2$/tonne (Broekens et al., 2011). These high values are reflective of the energy-intensive processes involved in extracting, processing, and transporting these materials. Consequently, a challenge is to identify the type of construction material that can be used to minimize the carbon emission and, meets the requirements for stability, while causing no harm to the environment.

The transportation of construction materials during execution contributes significantly to the overall carbon emissions of hydraulic structures. The distance materials are transported can exponentially increase the carbon footprint, particularly when sourced from remote quarries or international locations. Specifically, as outlined in the study by Broekens et al. (2011), the transportation of rock for breakwater construction assumes a scenario where rock is sourced approximately 500 km away from the construction site. This transportation significantly contributes to the project's carbon emissions. Multiple studies highlight the carbon dioxide emissions associated with these transportation practices, noting the use of diesel-powered heavy goods vehicles which are a common choice for such tasks (Broekens et al., 2011, Saravia de los Reyes et al., 2020). Similarly, the construction phase may involve marine or land-based equipment, or a hybrid approach combining both modalities. However, complications arise when transitioning between equipment types, particularly when considering the environmental benefits of alternative transport modalities. Factors like costs, workability and efficiency should be examined. The impact of such transitions extends beyond the immediate logistical considerations, affecting various aspects of project execution such as timelines, resource allocation, and overall feasibility (Arogundade et al., 2023). Finding a balance between the considerations is crucial for implementing eco-friendly construction equipment.

1.2.2. Advancing Breakwater Construction: Materials and Design Innovations

In the search for sustainable coastal defense structures, significant advancements in design and construction techniques are focusing on reducing greenhouse gas emissions. This is because carbon emissions are significantly generated by construction activities and material usage. During the operational phase, however, emissions are expected to be low. Various strategies can significantly influence the environmental impact. One effective method is optimizing the physical structure of breakwaters, such as employing steeper slopes which decrease the size of the base and consequently reduce material requirements. Traditional rubble mound breakwaters, usually having a slope between 1:1.5 to 1:3, can be designed with steeper slopes when using artificial armour units, potentially reaching a ratio of 1:1, which reduces the required materials but necessitates higher quality material for stability and interlocking (CIRIA et al., 2007). However, this is not always suitable due to geotechnical requirements.

Later, the stability formula by Hudson (1953) and Van der Meer (1988) became tools used in determining the specifications of the armour layer in coastal engineering. According to Hudson's equations, explained by Schiereck and Verhagen (Schiereck and Verhagen, 2019), the stability of the armour layer is directly related to the cube of the density of the submerged material, as denoted in equation 1.1. This means that even small increases in material density can lead to significant improvements in stability. Alternatively, keeping the size of the material consistent can achieve similar stability gains. Physical model tests support this relationship (Ito et al., 1995), showing that using higher-density concrete armour units can enhance stability and withstand stronger waves. Additionally, higher-density concrete allows for thinner layers while still maintaining breakwater stability, which conserves raw materials and could reduce armour unit size by up to five times (Van Gent et al., 2001).

$$M = \frac{1}{\triangle^3} \qquad \triangle = \frac{\rho_{water}}{\rho_{armour}} - 1 \tag{1.1}$$

Recent advancements in construction materials, particularly highlighted by the Icelandic-Type Berm Breakwater study conducted by Eskafi and Sigurdarson (2023), demonstrate a significant shift towards the use of locally sourced rock. The approach prioritizes materials obtained from local sources, minimizing long distance transport. Similarly, this approach significantly reduces the carbon emissions associated with transport. This study incorporates alternative, innovative materials that have a lower embodied carbon than traditional choices such as conventional concrete and quarried stone. Examples include recycled materials, such as concrete from demolition cites, that perform equally well in marine environments but are more sustainable.

Furthermore, design innovations are being implemented to reduce the amount of materials needed. The study from Eskafi and Sigurdarson (2023), introduces innovative geometric designs that require less material by distributing stress more efficiently across the structure. For example, using interlocking shapes that naturally dissipate wave energy reduces the need for massive, solid structures (Eskafi and Sigurdarson, 2023).

1.2.3. Addressing Knowledge Gaps in Sustainable Construction

Despite these promising advancements, there remain substantial knowledge gaps that must be addressed to fully realize the potential of low-carbon construction or reused materials. One major area of uncertainty lies in the long-term durability and performance of these innovative or reused materials under diverse environmental conditions (Foster, 2022). Research is needed to find out how these materials perform over extended periods, especially in face of climate change-induced stresses such as increased storm frequency and rising sea levels. Additionally, the impact of innovations in fuels and other types of transport on the overall sustainability of breakwater construction remains an area ready for exploration. The adoption of alternative fuels such as bio-diesel, electric, or hydrogen-powered vehicles, and vessels in construction logistics can significantly reduce carbon emissions (De Burca, 2023). However, the full environmental impacts of integrating these innovative transport solutions are not yet fully investigated.

Also, understanding the full environmental impacts of new construction materials and techniques is critical for sustainable construction and quantification of the emissions. Life-cycle Assessments (LCAs) are crucial in this effort, providing a detailed view of environmental impacts across a project's life-cycle. Multiple tools are available to quantify the effect on the LCA of the constructions. However, the effectiveness of LCAs is often limited by the variability in the databases they use, which can differ significantly in geographic relevance, data currency, and completeness. These variations can lead to inaccurate environmental impact assessments. Moreover, the methodological differences between tools may prioritize certain impacts over others, affecting outcome consistency (Dijkstra, 2020). Addressing these challenges requires selecting the right tool with the LCA databases that are up-to-date, comprehensive, and relevant to the specific geographical and technological context of each project.

The shift towards sustainable construction of breakwaters exposes critical knowledge gaps that require further exploration. These include understanding the applicability and limitations of innovative, low-carbon materials under diverse conditions, a detailed review of the benefits of alternative transportation methods, and the limitations of current life-cycle assessment (LCA) tools in accurately quantifying the differences between innovative construction materials. The identified knowledge gaps, such as the comprehensive environmental impacts of alternative fuels in construction logistics, underscore significant uncertainties in achieving sustainable construction practices. Specifically, there is a need to evaluate how the choice of LCA tools and their underlying databases affect the accuracy and reliability of the quantification of environmental impact. These gaps emphasize the need for an integrated approach that addresses both immediate and long-term sustainability challenges, contributing to the broader goal of sustainable development. This understanding led to the formulation of the research question focused on integrating various aspects to achieve carbon neutrality in breakwater construction.

1.3. Research Question

The research question, arising from the problem statement, is as follows:

How can an integrated approach effectively tackle the challenges posed by achieving carbon neutrality in breakwater construction, while ensuring project feasibility and sustainability?

Breaking down the research question:
The integrated approach signifies a comprehensive method that considers all aspects of breakwater construction-technical, economic, environmental, and operational-to optimize the entire process for improved sustainability and reduced carbon footprint. It emphasizes an integrated evaluation and solution framework rather than isolated improvements.
Sustainability refers to the ability of the construction practices to be maintained without exhausting resources or causing irreversible environmental damage by releasing microplastics, also in the long term.

The main research question will be answered by means of multiple sub-questions. Each sub-question emphasizing and tackling a different challenge included in the main research question. The sub-questions are stated below:

1. What tools are available to quantify the carbon emissions of breakwaters and what are the limitations and how can these be mitigated?
2. How can emissions due to transportation and construction equipment be reduced?
3. What materials can be identified and optimized for use in breakwater construction to minimize carbon emissions, ensuring both stability and water safety?
4. How can integrating sustainable and reused materials with innovative design approaches contribute to developing a carbon-neutral breakwater?

1.4. Approach and Reading Guide

Chapter 2 Literature Review: Analyzing Carbon Emissions in Modern Breakwater Construction
The second chapter includes an analysis of carbon emissions associated with each stage of the breakwater construction life-cycle, establishing a theoretical framework for this research. The chapter also covers methods for inventorying these emissions specifically within breakwater construction projects, providing insights in approaches used in other studies. Finally, it utilizes existing knowledge to address the challenges encountered when using various tools for quantifying carbon emissions in environmental impact evaluations, and thereby partly answering sub-question 1.

Chapter 3 The evaluation of equipment regarding CO_2-emissions
In this chapter, carbon emissions associated with transport and construction equipment are identified and alternative solutions are introduced, which answers sub-question 2. With the purpose of finding the optimal equipment utilization during the construction phase of the breakwater including the transport of construction materials.

Chapter 4 Material Inventory to reduce the carbon footprint
This chapter answers sub-question 3 and includes both literature study as well as a collaboration with companies and experts. In this chapter, both common materials and emerging or innovative materials are identified and evaluated on their application. Experts are approached for their vision on certain materials.

Chapter 5 Applying the Civil Engineering Elementary Design Approach for Carbon Neutral Breakwaters
Chapter 5 includes a systematical approach to evaluate materials and breakwater design concepts on various requirements and criteria, which will provide an answer to sub-question 4. It introduces additional techniques and adjustments to a general design approach that should be followed to eliminate designs and end up with the most suitable breakwater concept for any specific situation.

Chapter 6 Verification of the Design Approach: Case Study Braassemermeer
Chapter 6 introduces a case at the location of Braassemermeer, which will be used to validate and implement the previous identified methodology.

- The current circumstances are described. Including the dimensions and the hydraulic boundary conditions at that location.
- The most suitable design for the breakwater in the Braassemermeer is provided.
- An alternative is provided for a slightly different case.

Additionally, sub-question 1 will be addressed to indicate the impact of the calculation tool that is chosen.

Chapter 7 Discussion
Chapter 7 includes the discussion. In the discussion section, the findings are interpreted, by highlighting the significance and implications of the results. The outcomes are compared with outcomes of previous studies, discussing consistencies. This section also addresses the limitations of the study and suggest directions for future research, providing a broader context for understanding the research contributions.

Chapter 8 Conclusions
In chapter 8, the conclusions are presented. In this section, the main findings of the study are summarized, emphasizing the key outcomes and their relevance. The conclusion shortly restates the research objectives.

Chapter 9 Recommendations
Chapter 9 includes practical recommendations based on the study's results, suggesting specific actions or changes for further research to build on the study's contributions.

2

Literature Review: Analyzing Carbon Emissions in Modern Breakwater Construction

This literature review goes from the broader aspect of carbon emissions related to the life-cycle stages, to the the carbon emissions contributed by each element of a breakwater. Furthermore, it examines the carbon quantification tools. Overall, this will be valuable for the quantification of innovative materials and methodologies aimed at achieving carbon neutrality, which will be useful for the verification of materials in the case study.

2.1. Carbon emissions per life-cycle stage

While exploring various innovative design and construction techniques that reduce carbon emissions, quantifying the carbon emissions is an equally important step. Reducing the footprint of breakwaters, requires a deep understanding of the processes that contribute to the carbon emissions when constructing a breakwater. Five key stages can be distinguished during the construction process; construction materials, construction activities, operation, end-of-life stage and the additional benefits of reusing materials. Figure 2.1 shows a clear overview of the different stages and indicates the system boundaries (Broekens et al., 2011).

1. **Construction Materials [A1-A3]:** This involves the production, extraction, processing, and transportation of materials used in construction. Carbon emissions arise from energy-intensive processes like cement manufacturing, steel production, and extraction of raw materials such as aggregates and metals (Broekens et al., 2011).
2. **Transportation and Construction Activities [A4-A5]**: This category encompasses both the transportation of construction materials to the site and the on-site construction activities. Carbon emissions arise from the transportation of materials from their production sites to the project location, including emissions from vehicles such as trucks and ships. On-site construction activities, such as excavation, concrete pouring, steel erection, and machinery operation, also contribute to emissions. Additionally, energy consumption from construction equipment, generators, and lighting during construction adds to the carbon footprint.
3. **Operation and Maintenance [B1-B5]:** Beyond construction, ongoing operation and maintenance activities can generate carbon emissions. This includes energy consumption for powering equipment, pumps, and lighting in the operational phase, as well as maintenance activities such as repairs and replacements.
4. **Disposal at End of Design Life [C1-C4]:** At the end of a project's design life, materials and structures may need to be dismantled, demolished, or disposed of. This process generates carbon emissions from activities like demolition, waste transportation, and land-filling or recycling of materials.
5. **Reuse/Recycle Potential [D]:** Assessing the potential for reusing or recycling materials can significantly impact carbon emissions. Reusing materials from existing structures or incorporating recycled materials into new construction projects can reduce the need for new resource extraction,

manufacturing, and transportation, thus lowering carbon emissions associated with these activities. Identifying opportunities for reuse and recycling early in the project life-cycle can help maximize the environmental benefits and minimize waste generation (Dbrowska et al., 2023).

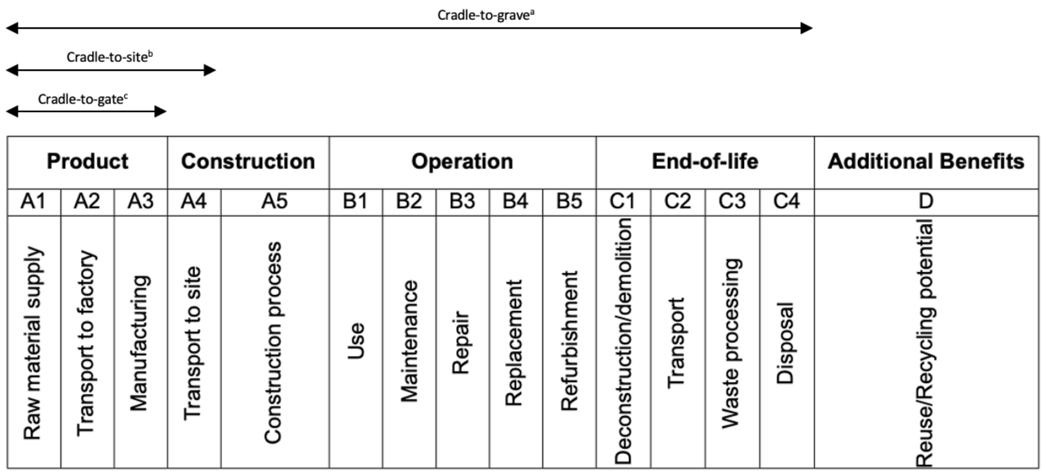


Figure 2.1: Sources of CO_2 emission in the stages of designing a breakwater
[a]Carbon released from the extraction of raw material until the end of the product lifetime
[b]Carbon released until the point of use
[c]Carbon released until the product leaves the factory

By addressing each of these key areas, strategies can be developed to minimize carbon emissions throughout the life-cycle of construction projects, promoting sustainability and environmental responsibility.

2.2. Inventorying of carbon emissions in breakwater construction

Current breakwater designs, such as rubble mound and concrete caisson types, have significant environmental impacts. Primarily due to their substantial carbon footprint, as revealed in detailed case studies by Broekens et al. (2011). This study shows that materials and transport are the largest contributors to the total Carbon Footprint of breakwaters, followed by the construction phase itself. The reason for that is that the construction of these coastal defenses involves extensive use of materials like rock, steel and concrete, which are associated with high levels of embodied carbon depending on the source and production processes. For instance, rock, a common material in such constructions, shows a wide range of embodied carbon values. Granite can have an embodied carbon value ranging from 6 to 781 $kgCO_2$ per tonne, depending on quarrying methods and stone type, while limestone is typically around 17 $kgCO_2$ per tonne (Broekens et al., 2011). Due to its softer nature it is easier to extract and process requiring less energy (Adhikari and Lewis, 2023). Indicating the impact a choice of material can have on the total carbon footprint of the breakwater.

Additionally, the transportation of these materials to construction sites often involves long distances and heavy machinery, contributing further to carbon emissions (Broekens et al., 2011). The construction phase itself, utilizing various land-based and marine equipment, also adds to the overall environmental impact. The operation of heavy machinery is necessary but results in high levels of direct carbon dioxide emissions. This emphasizes the high environmental costs associated with the life-cycle from material production to transportation and construction activities.

Furthermore, a life cycle approach, as detailed in the study conducted by Saravia de Los Reyes et al. (2020), includes the continuous emission of greenhouse gases throughout the operational life of the infrastructure. In contrast to the construction phase, which accounts for about 99% of the emissions, it is reported that the operation and maintenance phases together contribute only about 1% to the total emissions (Saravia de los Reyes et al., 2020). This relatively small percentage emphasizes that while the operational emissions are significantly lower, they still represent a minimal, but continuous environmental impact throughout the life-cycle of the infrastructure.

These analyses illustrate the need for integrating sustainable practices and technologies in coastal developments to mitigate their environmental impacts. Addressing the knowledge gap in comprehensive life-cycle assessments of alternative, less carbon-intensive materials and improving construction processes could significantly contribute to reducing the environmental impacts of coastal projects.

2.3. Challenges of Carbon Quantification Tools in Environmental Impact Evaluations

The comprehensive breakdown of carbon emissions from the life-cycle stages of breakwater construction sets the stage for a critical examination of how these emissions are quantified and assessed. It is crucial to evaluate the accuracy and effectiveness of the tools used to measure these emissions. The following section examines the challenges of current carbon quantification tools used in environmental impact assessments. It highlights the need for precise methodologies to ensure that the strategies employed to reduce emissions are based on reliable data.

In the literature review on carbon quantification tools for environmental impact assessments, various methods are explored to estimate the carbon footprint of construction materials and processes. The carbon footprint is an effective way of determining the levels of emissions generated. The carbon footprint (CF) can be calculated by means of equation 2.1 :

$$CF = \sum_{i=1}^{n} e_{t,i} * quantity_i \tag{2.1}$$

where n represents the number of these phases or activities and $e_{t,i}$ denotes the specific CO_2 emissions for each phase per quantity. The Carbon Footprint (CF) associated with the production of raw materials and their transportation is typically measured in kilograms of CO_2 per kilometer (kg CO_2/km) and per kilogram of material (kg CO_2/kg), respectively. The cumulative result of the CF is expressed in kilograms of CO_2 equivalents (CO_2-eq), which is the accepted standard unit for Carbon Footprint reporting (Labrujere and Verhagen, 2012). This facilitates comparisons across different structures. Another key metric discussed is embodied carbon, which encompasses the total emissions from the extraction, manufacturing, and transport of materials, providing a cradle-to-grave perspective.

Among the quantification methods, the Life-Cycle Assessment (LCA) stands out for its thorough approach in analyzing carbon emissions throughout the entire life-cycle of products and processes. Despite its detailed analysis, LCA is critiqued for not considering temporal variations, geographical specifications, and social or financial impacts, which may affect the outcomes. Various LCA software tools often differ in the impact categories they include and the normalization factors they use, introducing variability and uncertainty in the results. Additionally, data scarcity, especially concerning new materials, further complicates accurate assessments.

Specific tools like SimaPro and DuboCalc are highlighted for their application in LCAs. SimaPro is a product modeling and assessment software used to perform a LCA. The user is responsible for connecting the various data elements (e.g. transport distance). The tool uses the Ecoinvent database (Herrmann and Moltesen, 2015) and provides an accurate quantification of the carbon emissions with sufficient expertise. However, due to its manual method of connecting the data, it is a time-consuming tool.

Carbon calculators, such as DuboCalc, are often known as a more simplified method. These calculators are based on parameters and assumptions. No large-scale data collection is required for this method and it is often used on an organizational or personal level (Fasogbon and Igboabuchukwu, 2024). DuboCalc is a sector specific, simplified software. It is developed by both the Dutch government and Rijkswaterstaat and it makes use of the Dutch Environmental Database (NMD). NMD is specifically adapted from EcoInvent for the Dutch market. This adaptation focuses on local specifics such as transport distances, production, and energy use. NMD provides a more localized and precise dataset for Dutch construction projects, including tailored environmental impact data for products and processes. Furthermore, the tool makes use of pre-designed objects and is based on the Life Cycle Assessment. With the tool the environmental effects and energy usage of materials over their entire lifespan can be found, from cradle-to-grave.

On top of that, NMD is currently undergoing a transition. With the shift to the new European standard EN 15804+A2 in 2020, the NMD is moving towards a more comprehensive and scientifically rigorous approach to assessing the environmental impact of construction products. This transition involves revising product profiles based on the old standard, adopting a new set of environmental impact categories, and incorporating sub-indicators for deeper understanding. While the old set (set A1) comprises 11 environmental impact categories, the new set (set A2) includes 19, with further subdivision into sub-indicators. For instance, climate change, previously represented by a single indicator, is now divided into four sub-indicators to emphasize its importance, and new indicators have been added. Using the new set of categories affects the environmental profile of a construction product. As the NMD adapts to these changes, it is positioned to facilitate more informed decision-making and support the broader transition towards a sustainable and circular construction sector, not only within the Netherlands but also across Europe. However, not all materials have been revised yet according to the new standard and not all revised materials have been updated to the calculation tools such as DuboCalc. This may results in outdated information. For that reason, this study focuses on the data from Set A1, because that offers a more comprehensive overview. Data from Set A2, if available, will only be provided as reference.
Below, some limitations are given of DuboCalc:

- Not all materials and certainly not the innovative new materials are available in DuboCalc. This is due to the fact that suppliers are not obligated to have there materials in DuboCalc with the Environmental Cost Indicator (ECI) values. (Dijkstra, 2020)
- DuboCalc makes use of fixed values for transport distances related to different products. As transport distances have significant influence on the choice of materials, this should be adaptable. (van Rhede, 2019)
- DuboCalc works with an outdated version of the Dutch Environmental Database (NMD) and therefore lacks some information on materials. (Dijkstra, 2020)
- DuboCalc does not include carbon sequestration of materials (e.g. wood), which is included in the new set A2.

These limitations result in that companies create simplified calculation tools for themselves, using the data provided by the databases and tools. This does not necessarily mean that the values differ, but it can mitigate the limitations of current tools.
Understanding how the choice of carbon quantification tool affects the reliability of sustainability assessments can have a large impact on the outcome. Differences between tools like SimaPro and DuboCalc, due to varied methodologies and outdated or incomplete data, underscore the need for standardization and a comprehensive comparison to ensure accurate carbon footprint calculations. Both Dubocalc and SimaPro utilize the same background data but differ in their application and specificity. Dubocalc is more tailored for Dutch infrastructure projects, providing ready-made LCA data for various products, which simplifies the process for users. SimaPro, on the other hand, allows for detailed customization and adjustments, making it suitable for more complex or non-standard assessments.

2.4. Concluding Remarks

The literature review provides an in-depth examination of the carbon emissions associated with breakwater construction, covering various life-cycle stages, from material extraction to end-of-life disposal. The bulk of carbon emissions stems from material production and transportation, emphasizing the significant impact of choosing materials with lower embodied carbon values, which will mainly put the focus on the life-cycle stage A1-A5 in this report. The review also underscores the potential benefits of material reuse and recycling in reducing overall emissions.

A critical analysis of carbon quantification tools reveals substantial challenges and limitations. Life-Cycle Assessment (LCA) methods, while thorough, suffer from inconsistencies and data gaps, particularly with new materials, in the form of updated LCA calculations. Tools like SimaPro and DuboCalc, although useful, present their own set of issues related to data accuracy, adaptability, and comprehensiveness. The review calls for improved standardization and the integration of updated datasets to enhance the reliability and usability of these tools. For a better understanding, this research will focus on the application of the two calculation tools of SimaPro and Dubocalc.

This review provides guidance for optimizing design methodologies, material selection, and construction processes through creating focus points such as transport, materials, and quantification tools, to develop more sustainable breakwater solutions.

3

The Evaluation of Equipment regarding CO_2-emissions

In the search to design a carbon-neutral breakwater, evaluating the CO_2 emissions from construction equipment, is crucial to be able to recognize the hurdles. This chapter examines the role of heavy machinery and transport vehicles in the overall carbon footprint of the project. Sustainable technologies and fuel alternatives are explored to enhance equipment efficiency and reduce emissions. This analysis helps to answer sub-question 2, by identifying potential improvements, aligning with the goal of minimizing environmental impact and advancing towards a carbon-neutral construction process.

3.1. Introduction

More than 20% of the global CO_2 emissions is caused by the construction sector (Huang et al., 2018). The four main sources of direct emissions are the combustion of Diesel, Liquid Fuel Oil (LFO), Gasoline and other petrol (Huang et al., 2018). Analysis of construction's carbon footprint involves examining various phases including raw material extraction, manufacturing, transportation, installation, operation, maintenance, and disposal. Equipment plays a significant role in these phases. Considering the construction industry's substantial impact, there is a growing responsibility to reduce emissions to meet climate change goals. Consequently, reducing the CO_2 emission contribution by construction equipment alone could already have significant impact on the total emissions.

3.2. Conventional equipment

The transport of material to the site and onsite are often done by heavy goods vehicles (HGV), from which two types can be distinguished: rigid truck (>17tonne) and the articulated truck (>33tonne). In Table 3.1 the carbon emissions can be found per land-based equipment. Other land-based equipment discussed are excavators, dump trucks and a crawler crane. Note that the trucks used for transportation have a carbon emission related to their traveled distance, while the equipment used on site show emission of one complete machine day.

Table 3.1: CO_2 emissions of land-based construction machines.

Land-based machine	Carbon emission	Unit	Source
Rigid Truck	1.17	$kgCO_2/km$	(Broekens et al., 2011)
Articulated Truck	1.13	$kgCO_2/km$	(Broekens et al., 2011)
Dump Truck	128.73	$kgCO_2/md$	(Wu et al., 2019)
Excavator	198.4	$kgCO_2/md$	(Wu et al., 2019)
Crawler Crane	92.84	$kgCO_2/md$	(Wu et al., 2019)

The second type is the waterborne equipment. A very common waterborne equipment is the dredging vessel. Equipped with specialized machinery, these vessels excavate sediment from the seabed, collecting and the transport of materials to the construction site. This process is particularly advantageous for coastal projects as it allows for the utilization of locally sourced material, minimizing costs and environmental impact. The collected sediment from dredging vessels often becomes the infill material for the breakwater core. This localized sourcing enhances the breakwater's sustainability by reducing the need for transporting materials over long distances. Another waterborne equipment considered is the inland vessel that transports dry bulk consisting of sand and rock to the location via inland waterways. Another equipment mentioned is the floating crane. Floating cranes contribute to the precision and efficiency of breakwater construction. These waterborne cranes are used for positioning heavy components, such as concrete blocks or armour units, during the assembly of the breakwater structure. In Table 3.2 the carbon emissions related to these type of equipment are presented. For the floating crane, the amount of emission is assumed to be equal to that of the land-based crane.

Table 3.2: Carbon dioxide emissions of waterborne equipment.

Waterborne equipment	Carbon Emission	Unit	Source
Dredging vessel (short haul)	6.41	kg/tonne dredged material	(Aumônier et al., 2010)
Dredging vessel (long haul)	11.73	kg/tonne dredged material	(Aumônier et al., 2010)
Floating crane	92.84	kg/md	(Wu et al., 2019)
Inland shipping	45	g/tkm	(Anne Klein et al., 2021)

However, the primary source of maritime carbon emissions stems from fuel combustion, with heavy fuel oil (HFO) accounting for 77% of maritime fuel usage in 2013 (Tanzer et al., 2019). Figure 3.1 provides an overview of the contribution of conventional maritime fuels to carbon emissions based on various studies. It is evident from this overview that opting for greener fuels can significantly reduce total emissions. Despite the variability in results among studies, liquefied natural gas (LNG) demonstrates the potential to lower carbon emissions. The values represented in this figure denote the total grams of CO_2 emitted per MJ of fuel, reflecting emissions across the entire fuel production and utilization process, known as well-to-wake (WTW) values.

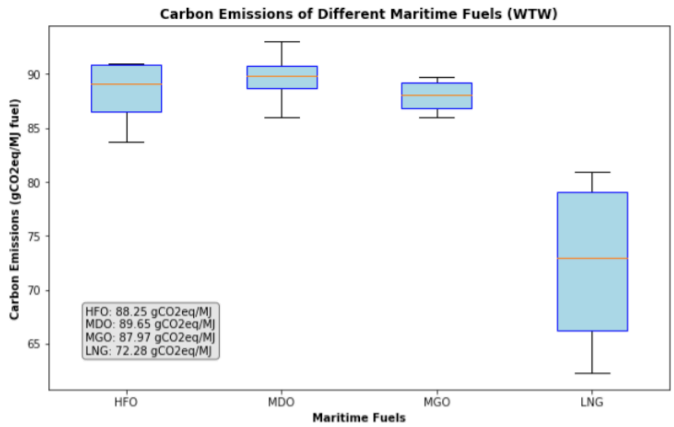


Figure 3.1: GHG Emissions of conventional fuels of maritime fuels [Sources: Foretich et al., 2021, van Lieshout et al., 2020, Hawkins et al., n.d., Sharafian et al., 2019, Pavlenko et al., 2020, Verbeek et al., 2011, International Maritime Organization, 2016]

3.3. Sustainable Fuel Alternatives for Lower Carbon Impact

In order to drastically reduce the emissions contributed by the construction equipment, the source of power needs to be revised. When generated through renewable energy sources, such as solar power and wind energy, electricity is the most popular eco-friendly power source. Electrification of the construction equipment is a popular innovative technology to lower the overall environmental impact. Equipment fully powered by electricity could bring the carbon emission during utilization back to zero. Especially land-based equipment has the potential of a full transition towards electrical powered vehicles. Manufacturers like Volvo, are presenting all-electric excavators that can enhance the growth towards a more sustainable construction industry (De Burca, 2023).

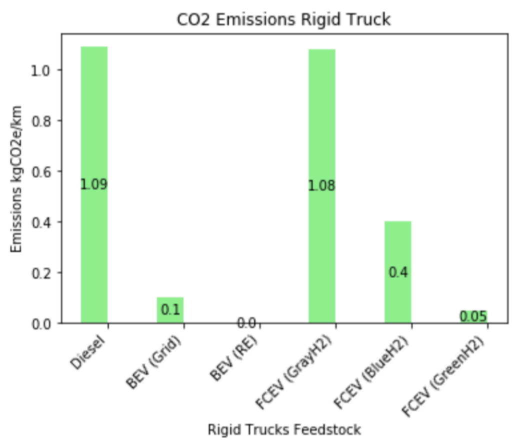
Other options could be the use hydrogen fuel cell or hybrid versions. The hybrid versions make use of multiple power sources like electricity and diesel, creating more power and a reduction in total carbon dioxide emissions. Hybrid models are often used in the form of excavators, due to capability of providing more power. Hydrogen fuel cells on the other hand, create zero emissions during operations. Nowadays, the technology is not that widely used, resulting in high costs (De Burca, 2023).

However, studies showed the feasibility of partially substituting diesel by hydrogen in heavy-duty engines. Experimental findings indicate that hydrogen enhances engine efficiency, particularly at higher loads, while significantly reducing carbon emissions and potentially minimizing harmful exhaust particles in the process. For instance, Barrios et al.(2017) successfully substituted 25% of diesel energy with hydrogen, resulting in a notable decrease in particle emissions. Recently, corporations introduced a minimal-conversion process allowing heavy-duty diesel trucks to operate on a blend of diesel and hydrogen, demonstrating the feasibility and reliability of this technology (El Hannach et al., 2019). Despite advancements, widespread adoption remains limited, necessitating solutions to market challenges for broader implementation of hydrogen-diesel dual-fuel systems.

Nevertheless, although limited, research has been done on the applicability of hydrogen and electricity on trucks in the future. A study done in the UK by Zemo Partnership concluded the advantages of implementing hydrogen in heavy goods vehicles (HGV) (Savage and Esposito, 2021). Hydrogen comes in different forms as green, blue and gray hydrogen. Gray hydrogen, produced from the reformation of natural gas without carbon capture and storage, is not preferred due to its higher well-to-wheel (WTW) greenhouse gas (GHG) emissions, which do not offer a significant improvement over diesel engines. On the other hand, green hydrogen, produced using renewable energy sources, presents a low-carbon alternative capable of significantly reducing WTW GHG emissions for hydrogen vehicles, making it a more sustainable option for the transport sector's move towards net-zero emissions. The study underscores the necessity of transitioning towards green hydrogen to get advantage from hydrogen vehicles' potential benefits in reducing carbon emissions and fighting climate change. Blue hydrogen represents an intermediate approach between gray and green hydrogen. Produced from natural gas through methane with the addition of carbon capture and storage, blue hydrogen aims to reduce carbon emissions associated with hydrogen production. While not as low-carbon as green hydrogen (which is produced entirely from renewable energy sources), blue hydrogen offers a significant reduction in WTW GHG emissions compared to gray hydrogen by capturing and storing the CO_2 emissions generated during the production process. This makes blue hydrogen a more environmentally friendly option than gray hydrogen and a feasible step towards the decarbonization of the transport sector. At this point the carbon emissions associated with gray hydrogen are similar to the carbon emissions related to diesel (Savage and Esposito, 2021). Figure 3.2 gives a summary of the carbon emissions associated with rigid trucks distinguished in battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV) having different feedstocks.

Rigid Truck (18 tonne)	**Feedstock**
BEV	Grid
BEV	Renewable Energy
FCEV Gray H_2	Fossil fuels
FCEV Blue H_2	Fossil fuels CO_2-capture
FCEV Green H_2	Renewable Energy

(a)



(b)

Figure 3.2: (a) Summary of the feedstock of potential fuels for HGV , (b) Carbon emissions related to different feedstocks of rigid trucks (Savage and Esposito, 2021)

Figure 3.2, indicates the potential of transitioning from diesel powered engines to full electric or hydrogen driven vehicles. Yet, the gray hydrogen should be avoided as this still includes the utilization of a lot of fossil fuels to produce.

Equally maritime equipment can change its source power to reduce the CO_2 emissions. There are many potential alternatives to the original fossil fuels. The most promising fuels are presented in Figure 3.3. In contrast to the conventional fuels, which have a carbon emission of 60 to 95 gCO_2/MJ, the alternative fuels have a significant lower emission rate of 0 to 60 gCO_2/MJ.

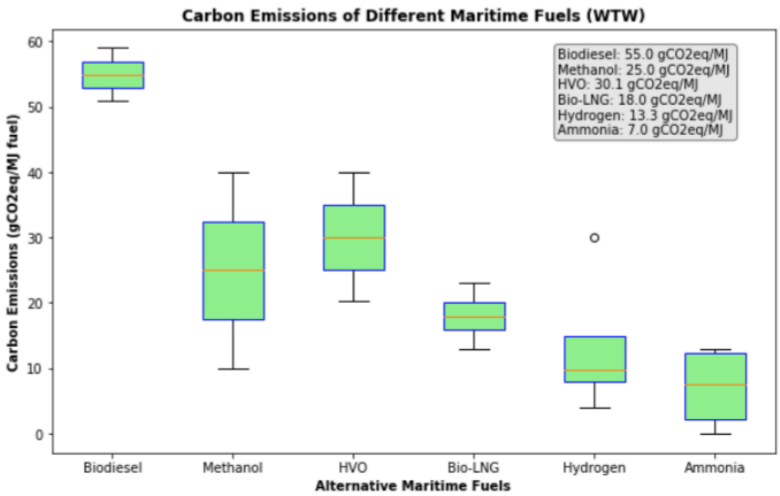


Figure 3.3: Boxplots: GHG Emissions of conventional fuels of maritime fuels [Sources: Foretich et al., 2021, International Maritime Organization, 2016, Xing et al., 2020, Garrain et al., 2010, Marquez, 2023, Comer et al., 2022, Konstantinos Kouzelis, 2021, Laursen and Patel, 2023, Laursen et al., 2023]

Biofuels, (e.g. biodiesel, bio-LNG, bio-methanol, Hydrotreated Vegetable Oil (HVO)) derive from biomass feedstocks, offering the potential for carbon neutrality as biomass absorbs CO_2 during its lifecycle (Cherubini et al., 2009). However, life cycle assessments demonstrate that bio-fuels are not entirely carbon-neutral due to significant upstream emissions from processing and transportation. Achieving carbon neutrality requires methods such as carbon offsetting or eliminating greenhouse gas emissions throughout the supply chain. Nevertheless, biofuels provide an opportunity to mitigate greenhouse gas emissions and enhance air quality in the maritime sector, given their minimal sulfur emissions. They are increasingly utilized in blends with fossil fuels to reduce emissions, although challenges concerning production capacity and cost persist.

3.4. Challenges

However, the transition to more environmentally friendly alternatives poses several challenges. Table 3.3 shows some limitations in the transition. The limited availability is the cause of the sudden high demand for environmental friendly vehicles. One way to mitigate this challenge is to change the sequence of the construction. Instead of simultaneously making progress with different phases of the construction, the next phases will need to wait till the equipment becomes available again. However, this is time consuming and will lead to higher construction costs. Additionally, the use of vehicles running on electricity require supporting infrastructure to make them useful. On site, the vehicles need enough charging facilities in order to prevent idle time due to lack of power.

Table 3.3: Advantages and limitations in transitioning to electrical driven land-based equipment

Advantages	**Challenges**
Long-term cost savings	High initial costs
Improving air quality on site	Supporting infrastructure required
Reducing noise pollution	Limited availability

Similarly, transitioning towards carbon-neutral waterborne equipment poses significant challenges, as can be seen in Table 3.4, particularly concerning the adoption of alternative fuels. While these fuels offer the potential to drastically reduce carbon emissions, several key obstacles must be addressed:

1. **Engine Compatibility:** One of the foremost challenges lies in ensuring compatibility between the new fuels and existing marine engines. Not all engines are designed to utilize low-emission fuels effectively, leading to potential inefficiencies in combustion and performance.
2. **Bunkering Infrastructure:** The availability of alternative fuels at ports is often limited by the lack of bunkering facilities. Establishing infrastructure for the storage and distribution of these fuels is crucial to their widespread adoption in the maritime industry.
3. **Storage Considerations:** Energy density plays a critical role in determining the storage requirements for alternative fuels. Fuels with lower energy densities necessitate larger volumes for equivalent transport work, impacting both range and onboard storage capacity. Therefore, storage solutions must be carefully designed to accommodate the specific properties of each fuel type (Appendix Foretich et al., 2021).
4. **Cost Competitiveness:** The economic viability of alternative fuels hinges on their cost competitiveness with conventional fuels. Initially, the higher costs associated with production, distribution, and infrastructure development pose significant barriers to widespread adoption. Overcoming this challenge requires combined efforts to drive down costs and stimulate investment in sustainable fuel solutions.

In conclusion, these sections have provided a comprehensive overview of carbon dioxide emissions stemming from equipment usage, distinguishing between conventional land-based and marine equipment and exploring more environmentally friendly alternatives. Through a comparison analysis, it has been demonstrated that equipment emissions significantly contribute to carbon footprints, underscoring the importance of adopting eco-friendly practices. The comparison between conventional and eco-friendly alternatives has highlighted the potential for reducing emissions and mitigating environmental impact. A switch to any of the alternative fuels reduces the overall environmental impact from marine fuels compared to use of HFO. Yet, this transition presents some challenges including the engine compatibility, expanding bunkering infrastructure, optimizing storage solutions, and driving down costs to promote the widespread adoption of sustainable fuel alternatives in the maritime industry.

Table 3.4: Challenges Correlated to each Fuel Type ((Hansson et al., 2019), (Foretich et al., 2021), (Parfomak et al., 2019))

Fuel Type	Challenges
Methanol	Few to no existing marine engines designed for use More expensive than LNG Potentially inefficient combustion
Biodiesel	Limited bunkering facilities and availability at ports More expensive than conventional diesel (MGO)
HVO	Limited bunkering facilities and availability at ports Currently too expensive
Ammonia	Limited bunkering facilities and availability at ports Potential challenges in storage and handling Currently too expensive
Hydrogen	Limited bunkering facilities and availability at ports Potential challenges in storage and handling
Bio-LNG	Limited compatibility with existing marine engines Limited LNG bunkering infrastructure at current ports

3.5. Transport Fuels on Total Construction Emissions

The potential of electricity and hydrogen from renewable energy to serve as a primary fuel for land-based and marine equipment offers a promising path for reducing carbon emissions in large-scale construction projects. This section evaluates the effects of a full transition to electric vehicles or hydrogen fuel on the carbon emissions of breakwater construction, dismissing current limitations and assuming complete utilization of the alternative fuels.

3.5.1. Land-based transport

For land-based vehicles a comparative analysis is applied on a case study examining the emissions from the construction of a conventional rubble mound breakwater with concrete armour units. Tables 3.5 and 3.6 give a summary of the emissions related to the construction of a conventional rubble mound breakwater. These values are based on assumptions made by Broekens et al. (2011), with embodied carbon emissions for rock and concrete being 5 and 80 $kgCO_2$/tonne, respectively. These assumptions include a transport distance from the quarry of approximately 500 km.

Table 3.5: Summary of EC for various construction materials (Broekens et al., 2011)

Material	Carbon Emissions ($kgCO_2$/tonne)	Rubble mound breakwater Quantity (tonne)
Rock	5	3 650 000
Concrete (armour units)	80	550 000
Total Carbon Emissions (million $kgCO_2$)		62

Table 3.6: Carbon footprint for rubble mound breakwater (Broekens et al., 2011)

	Rubble mound with concrete armour units
Materials (million $kgCO_2$)	62
Transport (million $kgCO_2$)	133
Construction (million $kgCO_2$)	17
Total (million $kgCO_2$)	212

The study indicates that the conventional rubble mound breakwater, despite lower emissions from material utilization, suffers from a higher overall carbon footprint due to significant transport emissions. The transport phase is especially carbon-intensive, constituting nearly two-thirds of the total emissions for the rubble mound breakwater. These transport-related emissions are currently based on diesel-powered trucks, generating 1.09 $kgCO_2/km$ and 1.14 $kgCO_2/km$ for different truck categories (Defra/DECC's, 2009).

To visualise the impact of a transition to other fuels, we project the case study data onto scenarios using hydrogen and electric-powered equipment. We conservatively assume the use of hydrogen-fueled rigid trucks with a capacity of more than 17 tonnes, holding a payload of 32 tonnes, and maintain the same emission values for fully laden as well as empty trucks. It is presumed that the carbon footprint for materials and construction remains unchanged.

Figure 3.4 demonstrates the relationship between the total carbon footprint of the rubble mound breakwater and the utilization of different fuels. The figure illustrates the expected reduction in carbon emissions when replacing diesel with hydrogen or electric engines for the transportation of construction materials over set distances.

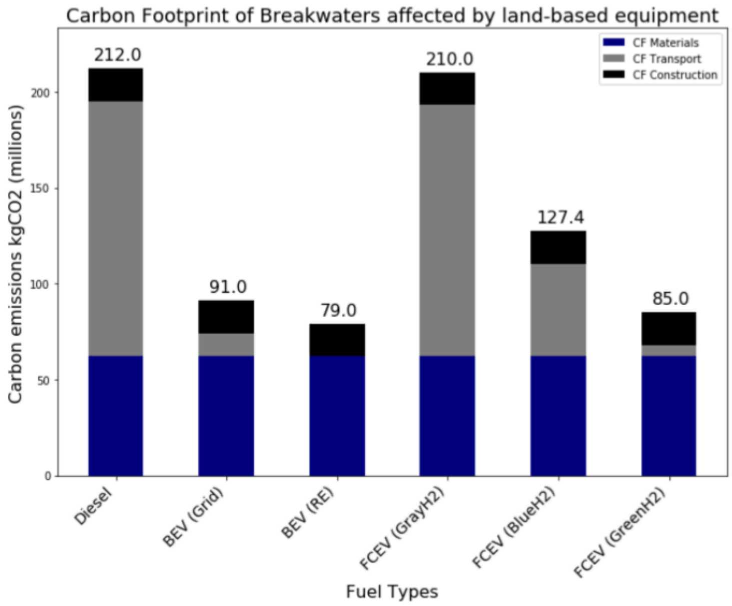


Figure 3.4: Change of transport fuel on the total carbon footprint of the breakwater

The case study's conclusions underscore the implications of fuel choice on carbon emissions in construction. While material-related emissions have been a center of attention, the transport phase presents an equally significant opportunity for emission reduction. The transition to hydrogen, as an alternative to diesel in heavy equipment, emerges as an effective strategy to lower the environmental impact of constructing breakwater projects. Besides the varying fuels, Figure 3.5, schematises the relationship between the total carbon footprint of a breakwater concerning the different fuels and the transport distances.
The carbon footprints associated with diesel and gray hydrogen are closely aligned, suggesting minimal emissions benefit when using gray hydrogen (GrayH2) compared to traditional diesel. In contrast, electricity from the grid and green hydrogen (GreenH2) display markedly lower emissions, underscoring the potential environmental advantages of electric and green hydrogen-powered vehicles. Notably, electricity from renewable energy (RE) demonstrates the smallest carbon footprint, indicating that renewable energy-powered electric vehicles are the most effective in reducing emissions. Blue hydrogen, despite including carbon capture, results in large emissions at greater distances, highlighting the limitations of blue hydrogen in reducing emissions effectively. It still needs to be noted that this graph is based on previously stated assumptions. Besides, although electricity from renewable energy sources could make the most impact, the limitations in the form of charging time and limited driving ranges could change the preference to green hydrogen. Overall, the data underscores the importance for the adoption of renewable energy sources in transport to significantly minimise carbon emissions.

The relative impact of required volume and different distances to the quarry on the total carbon footprint of a rubble mound breakwater is schematised in Figure 3.6. In these subplots, diesel is considered

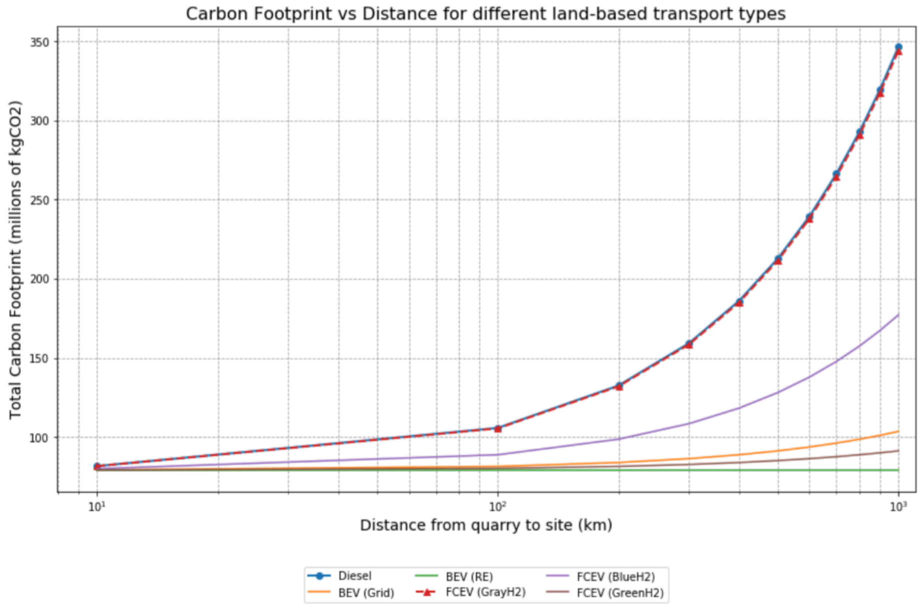


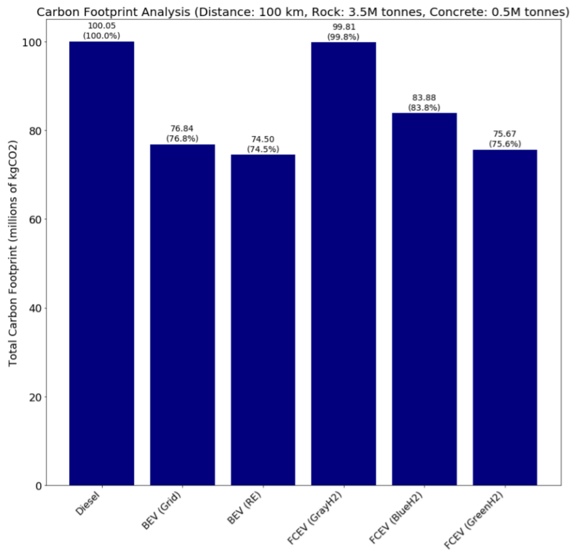
Figure 3.5: The impact of the distance from the quarry to the site per fuel on the total carbon footprint of the breakwater.

as 100% and for every other fuel the percentage relative to diesel is given to indicate the impact. For example, for small distances the impact of transitioning to electric vehicles running on renewable energy or green hydrogen can mean a reduction of 20% of the total carbon footprint.

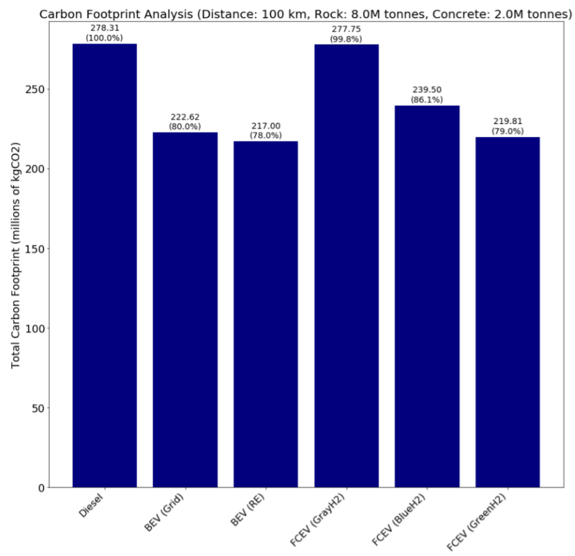
Examining the multiple sets of bar graphs provided, which show carbon footprint analyses for transporting different volumes over distances of 100 km to 1000 km, we can determine the relative impact of distance and volume on the total carbon emissions. For the smaller volume (3.5M tonnes of rock and 0.5M tonnes of concrete), increasing the distance tenfold from 100 km to 1000 km leads to a significant increase in carbon emissions. This is visually possible as the emission bars are considerably higher for the 1000 km distance. When the volume is increased (to 8.0M tonnes of rock and 2.0M tonnes of concrete), the increase in emissions is even more pronounced. This indicates that while distance certainly has a substantial impact on emissions, the increase in volume results in a larger relative increase in emissions.

For instance, if we compare the emissions from small volume at 100 km to large volumes at the same distance, there is a noticeable jump in total emissions, which becomes even more pronounced at the longer distance of 1000 km. This suggests that volume has a boosting effect on the impact of distance on total emissions.

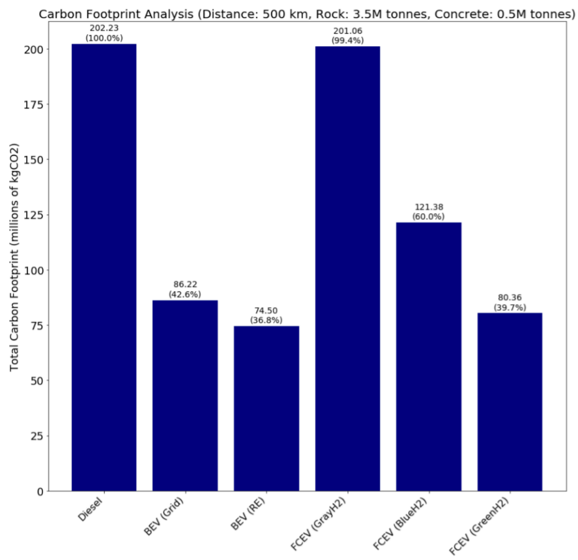
In conclusion, while both distance and volume have significant effects on the total carbon footprint of transporting construction materials, volume appears to have the most pronounced impact. The data suggests a progressive effect, where an increase in volume amplifies the carbon emissions not just in absolute terms, but also in how they scale with distance. This indicates that strategies for reducing carbon footprints in construction logistics should prioritize optimizing material volumes and consider the exponential impact of increasing both the volume of materials and the distance they are transported. The combination of volume, distance, and fuel type plays a crucial role in the carbon footprint of material transportation and production. These factors have a compound effect, where increases in volume and distance lead to a more than proportional increase in carbon emissions. This underscores the importance of optimizing fuel usage across all stages of material handling, especially in production, and considering the efficiency of transport logistics to minimize the environmental impact.



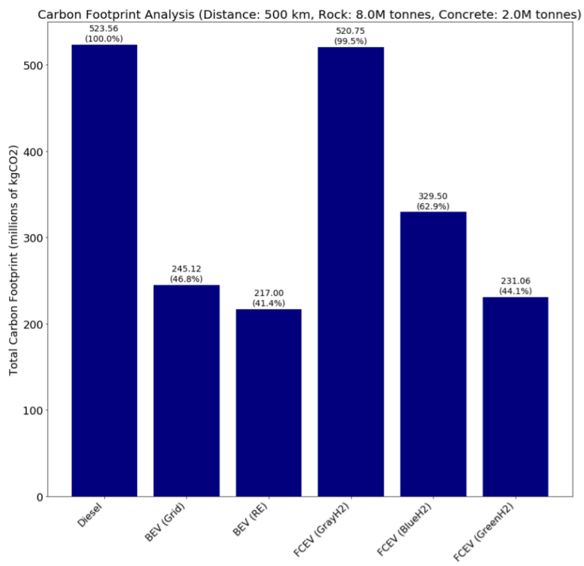
(a) Distance 100 km & small volume



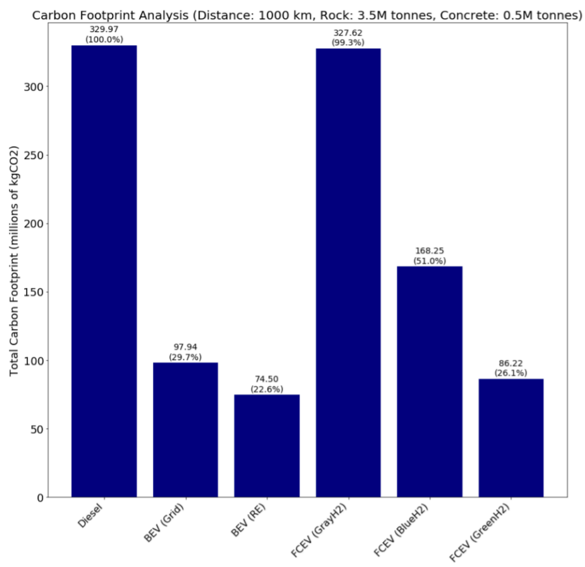
(b) Distance 100 km & large volume



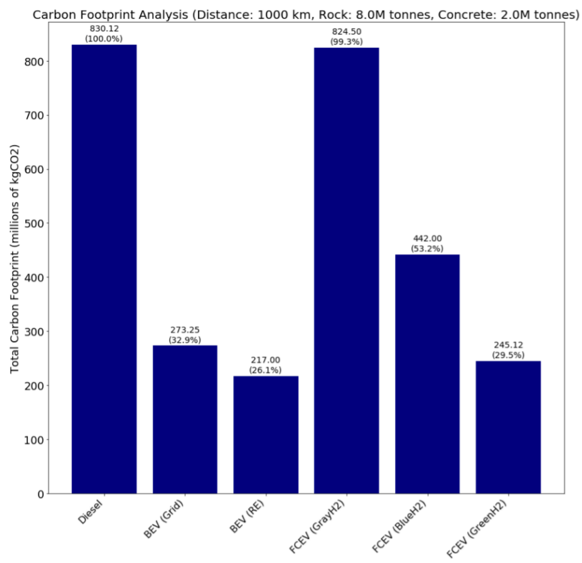
(c) Distance 500 km & small volume



(d) Distance 500 km & large volume



(e) Distance 1000 km & small volume



(f) Distance 1000 km & large volume

Figure 3.6: The impact of transport distance and required volume on the total carbon footprint of rubble mound breakwaters using rigid trucks

3.5.2. Maritime transport

Maritime transport is a major component of global logistics and contributes significantly to transportation emissions. Understanding and comparing the emissions from various fuel types used in maritime transport is critical for conducting environmental analyses and informing policy decisions.
For bulk carriers, which are vessels that transport unpackaged bulk cargo, capacities can range between 10,000 to 35,000 Deadweight Tonnage (DWT) (Anne Klein et al., 2021). The specific energy consumption of a vessel is a measure of the energy efficiency related to transportation work. In this context, we consider the specific energy consumption for bulk carriers with capacities of 20,000 to more then 50,000 DWT. The specific energy consumption for carriers with a capcity of 28,000 tonne is 0.09 Megajoules per tonne-kilometer (MJ/tkm) (Anne Klein et al., 2021).
When operating on Heavy Fuel Oil (HFO),carbon emissions can be calculated based on the fuel's carbon intensity. The carbon intensity of HFO is approximately 95 grams of CO_2 per Megajoule (gCO_2/MJ). Therefore, the carbon emission for a bulk carrier using HFO is computed by multiplying the specific energy consumption by the carbon intensity of HFO, resulting in 0.085 $kgCO_2/tkm$. Similarly in the case of hydrogen, the carbon emissions are significantly different. Assuming that the specific energy consumption of hydrogen is equivalent to that of HFO, and that the carbon intensity of hydrogen is approximately 13.3 gCO_2/MJ, from Figure 3.3, the emissions are calculated as:

$$\text{Hydrogen carbon emissions} = 0.013\frac{\text{kgCO}_2}{\text{MJ}} \times 0.09\frac{\text{MJ}}{\text{tkm}} = 0.0012\frac{\text{kgCO}_2}{\text{tkm}}$$

Figure 3.7, illustrates that for land-based electric vehicles (BEVs), hydrogen fuel cell vehicles (FCEVs), and maritime hydrogen-powered vessels, the carbon footprint increases with both distance and volume. BEVs, powered by renewable energy, consistently show the lowest carbon footprint due to zero operational emissions. Maritime transport, despite starting with a higher footprint than BEVs, remains more carbon-efficient than FCEVs at all examined volumes. This efficiency becomes more pronounced with larger volumes, especially over longer distances, as indicated by the maritime line's gentler slope in the graphs. Consequently, maritime transport becomes increasingly advantageous with scale, affirming the effectiveness of larger vessels in reducing the carbon footprint per tonne.

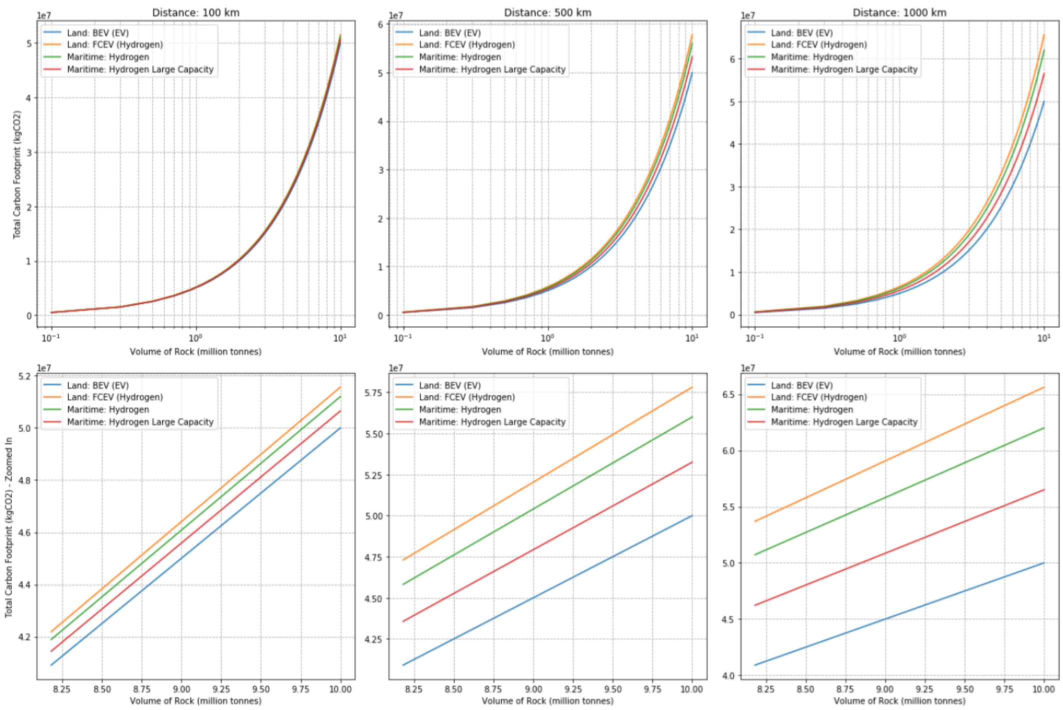


Figure 3.7: The total carbon footprint associated with transporting various volumes using different modes of transportation (land-based electric vehicles (BEVs), land-based hydrogen fuel cell vehicles (FCEVs), and maritime hydrogen-powered vessels) across three different distances (100 km, 500 km, and 1000 km).

Note: The specific energy consumption of hydrogen engines in ships is not known yet en therefore assumed as equally efficient as the HFO engines.

3.6. Innovative Solution to Lower Carbon Emissions at Construction Sites

3.6.1. Introduction

A sustainable shift in the industry is the adoption of electric and hydrogen-powered construction machinery used onsite. This shift not only helps in reducing the reliance on fossil fuels but also decreases emissions substantially. Advanced energy solutions, such as hydrogen fuel cells and large-capacity battery systems (see Figure 3.8), are now being developed to power heavy machinery effectively. These cells convert hydrogen into electricity, providing clean, efficient power for heavy machinery such as excavators and cranes, resulting in zero carbon emissions during operations. The versatility and scalability of hydrogen fuel cell technology make it suitable for a wide range of construction environments, from small residential projects to large-scale infrastructure developments. This section provides more details, advantages and limitations of this innovation.

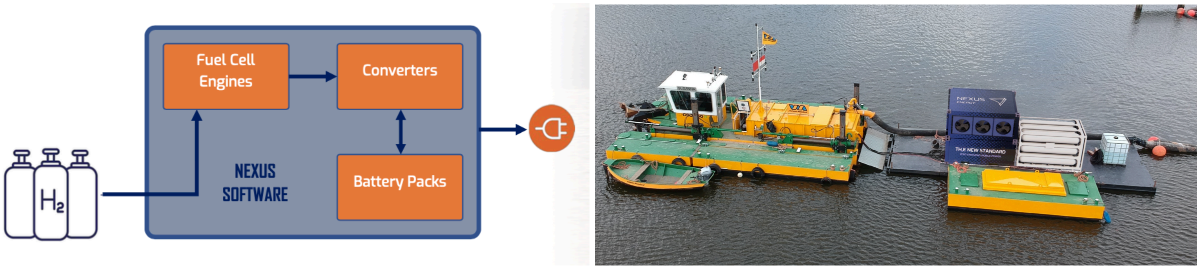
Figure 3.8: Powercell Hydrogen (Nexus Energy B.V.)

3.6.2. Advantages of Hydrogen and Electric Energy Solutions in Construction

The most significant advantage of integrating hydrogen and electric systems into construction is clearly their ability to operate with zero emissions. This characteristic is crucial as industries worldwide push towards reducing their carbon footprints to meet global environmental standards. Nexus Energy BV's fuel cell technology is an example of how these systems can sustain high energy efficiency, converting hydrogen into electricity without the byproducts of combustion, thus eliminating on-site carbon emissions.

Furthermore, the application is very wide, due to the container's capacity offering a continuous power output capacity of 120 kW, with the ability to peak at higher outputs such as 200 kW when required. A hydrogen container holding 400 kg of hydrogen can store a total of 7200 kWh of energy after conversion (400 kg $\times$ 18 kWh/kg) (Interview B.4). Electric vehicles have different capacities, varying per size. Heijmans has for example, a fully electric excavator with a capacity of 260 kWh which can be used for smaller projects (Heijmans, 2024).

However, heavy duty equipment often includes a larger battery capacity ranging from 300 to 400 kWh (Interview B.4). An excavator with an average battery capacity of 350 kWh can be fully charged around 20 times using the energy from this hydrogen container (7200 kWh $\div$ 350 kWh = 20.57). The charging times for each scenario vary, based on the charging power. Currently, it takes about 2.9 hours to fully charge an excavator at a constant rate of 120 kW, but peak charging at 200 kW reduces this to 1.75



(a) Schematization of the Fuel Cell System

(b) Maritime application of the fuel cell

Figure 3.9: Fuel Cell Nexus Energy B.V.

hours. Next year, the charging power will increase to 250 kW, reducing the time to 1.4 hours, and peak charging at 400 kW will cut this further to 0.9 hours, as depicted in Figure 3.10. One fully charged excavator can operate for a full day (8 hours) (Interview B.4). The hydrogen container can sustain a single excavator with a battery capacity of 350 kWh for around 20 days, when charged over night. With increasing numbers of excavators, the operating days decrease proportionally, such that five excavators with similar capacity would exhaust the container's energy in about 4 days.

Figure 3.11, shows how long the hydrogen container would last with varying numbers of equipment and with varying capacities. Besides, the compactness of such a 10 ft container makes it easy to transport and install, even on maritime equipment, see Figure 3.9.

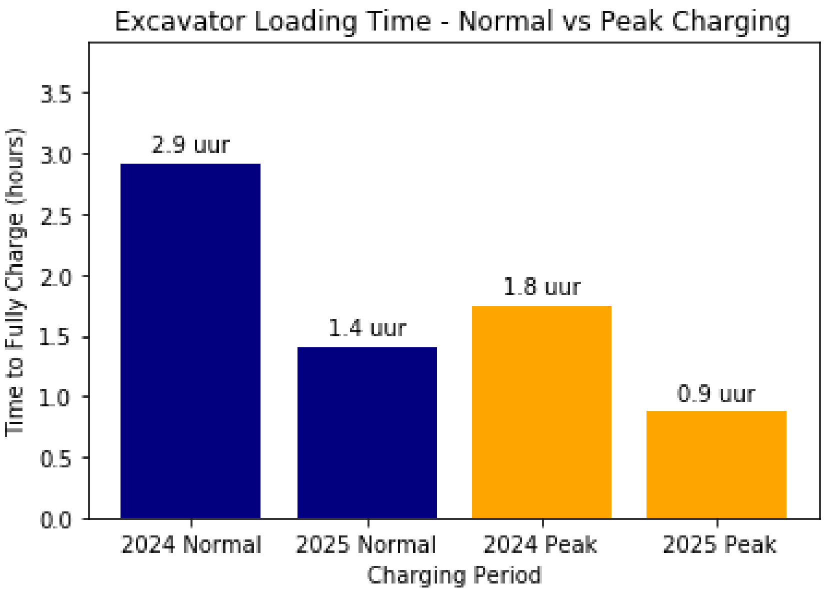


Figure 3.10: Time it requires to fully recharge with a battery capacity of 350 kWh

Lastly, another advantage is the cost-efficiency. A liter of diesel contains 10 kWh of energy, but diesel engines typically achieve only about 35% efficiency at their optimal point in the torque-speed curve. This ideal operating condition is rarely used because the engine would consume too much fuel, and the motor often runs at idle speed, which is inefficient. Studies estimate the overall efficiency of diesel engines, considering actual usable energy and not just the mechanical process of energy conversion, to be around 20% (de Ruiter and Bhoraskar, 2023). HVO, currently costs approximately €1.80 per liter. With an efficiency of 20% over 10 kWh, this provides a net energy output of 2 kWh per liter, making the cost €0.90 per kWh. Red diesel, which is untaxed, costs around €0.80 per liter and thus about €0.40 per kWh (Interview B.4).

In comparison, hydrogen is priced between €10 and €13 per kilogram in smaller volumes, and in larger quantities, it can drop to €8. One kilogram of hydrogen contains 33 kWh of energy, and fuel cells convert it to electricity with an average efficiency of 55%. Unlike diesel engines, fuel cells do not incur efficiency losses from idling. Therefore, 33 kWh multiplied by 0.55 yields 18.15 kWh per kilogram of hydrogen. The

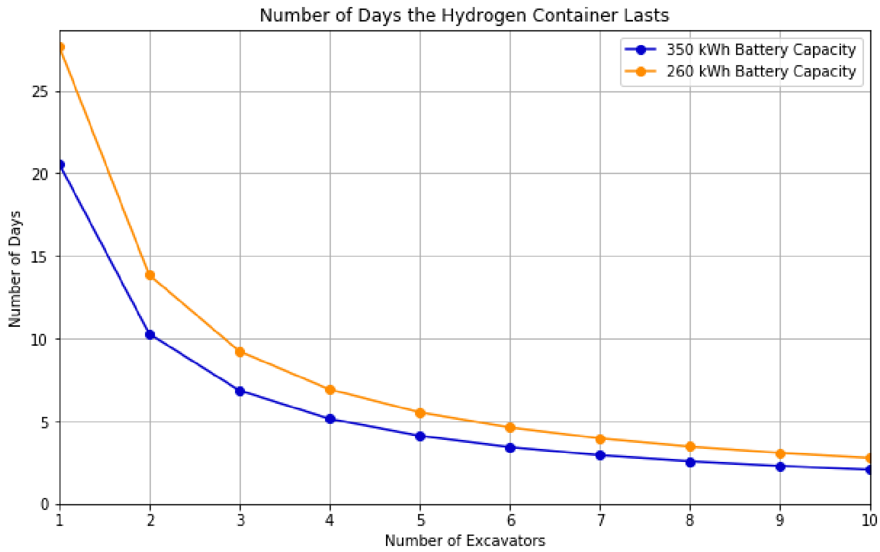


Figure 3.11: Number of days the hydrogen container lasts vs amount of equipment used with varying battery capacities

cost per kWh for hydrogen is approximately €0.70 (at €13/kg) or €0.44 (at €8/kg) (Interview B.4). On top of that, additional costs will be included for using polluting fuels like diesel, due to the CO_2-rights (Emissieautoriteit, 2023), making hydrogen an even more favourable option.

3.6.3. Limitations of Hydrogen and Electric Energy Solutions in Construction

Current technology for hydrogen storage and electric batteries does present challenges. Hydrogen needs to be stored under high pressure, raising safety and logistical concerns. The challenge with hydrogen is not its energy content per volume unit, which is actually quite high, but rather the large physical space that this volume occupies. This high volume-to-energy ratio means that to make hydrogen storage more practical and efficient, it must be compressed, liquefied, or converted into a carrier such as ammonia. However, these technologies are still in the early stages of development. Currently, we are able to utilize gaseous hydrogen effectively to generate power, demonstrating the potential and utility of hydrogen in its simplest form.

Additionally, the construction sector is still adapting to the use of hydrogen and electric technologies, with ongoing developments needed to enhance their effectiveness and efficiency. Regulatory frameworks specific to the safe and widespread use of hydrogen in particular, are still in development. This evolving regulatory landscape can pose challenges regarding compliance and operational permissions. Moreover, the market for hydrogen and electric construction machinery is not yet fully mature, which may influence the availability and continual improvement of these technologies. In addition, companies still chose the safe and known options over the unknown and less usual option.

3.6.4. Future Outlook and Advancements

The future looks promising as ongoing advancements in technology continue to improve the efficiency and capacity of these power systems. Developments in energy density are expected to double the output within the same physical footprint, offering even greater benefits. The storage capacity will increase to one megawatt per 10 ft container in the next year according to Nexus Energy B.V. Additionally, the power supply is improving. The fuel cell now is capable of continuously supplying 120 kW and peaks of 200 kW. However, at the end of 2024 it is expected that these same fuel cells will be able to supply 250 kW continuously and 400 kW during peak moments.

Moreover, the hydrogen storage system described, offers significant adaptability and future-proofing by supplying the hydrogen storage component separately from the power generation unit. This modular approach allows for tailored storage solutions specific to different applications, such as varying demands of construction sites or stationary installations. It also facilitates easy upgrades to accommodate ad-

vancements in hydrogen storage technology, such as transitioning from gaseous to solid storage forms or incorporating materials like Liquid Organic Hydrogen Carriers (LOHC). This design ensures that the system can evolve with emerging technologies, extending its operational lifespan and enhancing its efficiency and safety without requiring a complete replacement. Current limitations include the limited capacity of hydrogen containers when used with multiple pieces of equipment. For smaller projects utilizing up to three comparable machines like excavators, this option becomes profitable, as the container can provide hydrogen for over a week. However, for larger projects with more heavy-duty equipment, the same container will not last as long, potentially causing downtime. While the availability of hydrogen containers is increasing annually, further improvements are necessary to ensure long-term profitability.
Lastly, hydrogen becomes particularly profitable for construction sites consuming more than 300 liters of diesel per day. Diesel engines, often operating at around 20% efficiency due to sub-optimal operating conditions and idling, provide only 2 kWh of usable energy per liter of diesel. With diesel priced at approximately €2 per liter for HVO 100, the cost per kWh is around €1. In contrast, hydrogen provides a more efficient and cost-effective energy source at 40-50 cents per kWh, making it already a financially viable option.

The adoption of electric and hydrogen-powered machinery in the construction industry represents a proactive approach to environmental conservation and operational efficiency. As the technology evolves and becomes more cost-effective, it is likely to become a standard, replacing traditional diesel-powered equipment and significantly reducing the industry's carbon footprint. This transition not only supports global sustainability goals but also offers economic benefits by lowering long-term operational costs.

3.7. Concluding Remarks

The evaluation of equipment regarding CO_2 emissions in the transport and construction of carbon-neutral breakwaters highlights significant challenges and opportunities. Despite the substantial environmental benefits, several factors hinder the immediate transition to CO_2-neutral construction equipment.

Firstly, transitioning to electric and hydrogen-powered machinery involves high initial investments. The cost of buying new equipment and establishing necessary infrastructure, such as charging stations and hydrogen bunkering facilities, is substantial. Additionally, the current market availability of eco-friendly construction machinery is limited, which delays project timelines and increases costs due to phased construction approaches.

Moreover, electric vehicles require a robust charging infrastructure that is often lacking on construction sites. Similarly, hydrogen-powered equipment faces challenges in fuel storage and distribution, needing high-pressure systems and safety protocols. Engine compatibility issues further complicate the use of alternative fuels. Especially in maritime equipment, because ships and other marine vessels often use large, specialized engines that are difficult and expensive to modify. As a result, it may be more practical to design and build new engines specifically for alternative fuels rather than attempting to modify existing ones.

Furthermore, the efficiency of electric and hydrogen-powered machinery is still evolving. Electric equipment, while reducing emissions to zero during operation, often faces limitations in battery life and charging time. Hydrogen fuel cell power stations, although promising, are not yet widely adopted due to high costs of suitable equipment and logistical challenges in storage and handling. Currently, electric machinery suits small to medium projects due to limited power stations, which use hydrogen to generate electricity for recharging equipment. Small projects with up to three machines can use a single hydrogen container for over a week. Larger projects need multiple power stations to prevent downtime.

However, there is a need for more extensive life cycle assessments that account for the production, operation, and disposal phases of alternative fuel technologies. Current studies primarily focus on operational emissions, neglecting the environmental impact of manufacturing and end-of-life disposal. For example, producing batteries for electric vehicles involves significant mining activities, which can lead to habitat destruction, water pollution, and other environmental harms. Similarly, the disposal of these batteries can pose environmental challenges if not managed properly.

Additionally, research on the scalability of green hydrogen and other sustainable fuels is limited. While small-scale implementations show promise, there is insufficient data on the performance and feasibility of these technologies in large-scale, long-duration projects typical of breakwater construction.

Besides, the long-term economic benefits of transitioning to sustainable fuels are not well-documented. Detailed cost-benefit analyses that consider factors such as fuel prices, maintenance costs, and potential operational savings are crucial for encouraging widespread adoption.

Ongoing developments in hydrogen storage technology, such as the use of Liquid Organic Hydrogen Carriers (LOHC), need further exploration. The potential of these technologies to improve energy density and reduce logistical challenges is significant but requires more research and real-world testing.

Moreover, the regulations for hydrogen and electric-powered construction machinery is still developing. Clear guidelines from policymakers could accelerate the adoption of these technologies. Research into the effectiveness of different policy measures and their impact on the construction industry is necessary.

Lastly, there is a gap in knowledge regarding the integration of new technologies with existing construction practices. Studies that explore best practices for combining traditional and alternative fuel machinery can provide valuable insights into making the transition smoother and more efficient.

In conclusion, while the path to CO_2-neutral breakwaters presents several challenges, including high costs, infrastructural demands, and technological limitations, the potential benefits in terms of reduced emissions and long-term operational savings are substantial. Addressing these issues through comprehensive research, policy support, and technological innovation is crucial for advancing towards sustainable construction practices.

4
Material Inventory to reduce the Carbon Footprint

This chapter creates an inventory by means of a critical evaluation of materials used in the construction of breakwaters, emphasizing both traditional options like concrete and rock, and innovative alternatives that hold promise for environmental sustainability. This analysis begins with the impact of material volume and follows with an assessment of the environmental impacts associated with conventional materials and progressively shifts focus towards potential materials that could play a crucial role in reducing or even neutralizing carbon emissions in coastal engineering projects.

4.1. Material Volume

Material volume is a crucial parameter in the design of carbon-neutral breakwaters, as minimizing volume efficiently reduces carbon emissions. While some structures, like sheet piles, can minimize material use, they face significant limitations. Breakwaters need sufficient mass and weight to resist significant wave forces and ensure stability. Lighter materials or thinner designs often lack the required structural integrity, making them vulnerable to displacement and damage. Additionally, materials like wood and steel present durability issues; wood may not be durable enough, and steel is highly prone to corrosion in marine environments, necessitating frequent maintenance (Istiyanto et al., 2021).

To achieve the desired stability, a substantial amount of steel would be needed, which is not ideal due to its environmental impact. Moreover, thin, vertical designs primarily reflect wave energy, causing turbulence and potential erosion and scour (Istiyanto et al., 2021). Consequently, despite their potential for reducing material usage, such designs alone are impractical for effective and sustainable breakwater construction.

For that reason, conventional breakwaters often consist of a large volume of materials. Often, multiple types of materials are required to fulfill the desired functions. The primary functions of the materials used in breakwaters are:

- providing foundation and filtering facilities
- providing volume filling
- protect structure against wave and/or current action

A range of materials is evaluated, from well-established to emerging, assessing their functionality in various components of breakwater construction such as core, armour layer, filter layer, and bed protection. As depicted in Table 4.1 the materials and their applications are mapped out.

Table 4.1: Conventional materials in hydraulic engineering

Materials	Conventional Breakwater Components				Other Structures
	Core	Armour layer	Filter layer	Fascine Mattress	
Concrete	X	X			
Rock	X	X	X		
Polymer Concrete	X	X			
MagnaDense Concrete	X	X			
Geotextile (Tubes)	X	X	X	X	
Bamboo					X
Timber					X
Brushwood	X			X	
Blast Furnace Slag	X				
Steel					X

4.2. Commonly used materials

4.2.1. Natural Rock

The materials commonly used in large volumes for conventional breakwaters include concrete units, natural rock, and alternative granular materials. The use of these materials does contribute significantly to the total GHG emissions of the breakwaters nowadays. For the acquiring of rubble stone, there will be looked at the cradle-to-cradle value (Lifecycle stages A to D, see Figure 2.1). Rock can be applied in multiple variations from armour to core material. In Table 4.2, an overview is provided for values achieved from the Dutch Environmental Database (NMD, Branco Schipper and Hövel, 2021). The use and maintenance phase are negligible because natural rocks don't require any maintenance and are not contributing to any carbon emissions when used. Moreover, the NMD makes use of a fixed transport distance for the calculation of lifecycle phase A4. As most natural rock used in the Netherlands is provided by German or Belgium quarries, the distance of 200 km is used (Branco Schipper and Hövel, 2021). The NMD does not specify the stone type, but limestone is assumed, as it is common in Belgian and German quarries. Additionally, 90% of the rubble rock can be recycled when it is used as armour layer. However, when fine rocks are used in filter layers or as core material, none can be recycled. Consequently, having a larger carbon footprint.

Table 4.2: Carbon Footprint of Rubble Stone per m^3

Rubble stone	$kgCO_2/m^3$	Database
Armour Layer	22.26	NMD
Core Material	31.14	NMD

Although, the durability of rock is estimated to be around 100 years, it still shows some degradation over time. The durability of armour stone is quantified by its ability to retain mass over time under environmental stressors. According to the CIRIA Rock Manual, degradation models such as the Micro-Deval (MDE) and Armour stone Quality Designation (AQD) methods provide estimates for mass loss. For limestone, the AQD method suggests that armour stone of different initial sizes (0.5 tonnes, 1.5 tonnes, and 3.0 tonnes) retains a fraction of its original mass after 50 years. Specifically, 0.5 tonne rocks retain 69% to 75% of their original mass, 1.5 tonne rocks retain 76% to 80%, and 3.0 tonne rocks retain 80% to 83% (Caricato et al., 2011). Extrapolating these results to a 100-year lifespan, the degradation rates suggest that smaller rocks would retain even less of their original mass, highlighting the need for robust initial design choices.

Larger rocks degrade at a slower rate compared to smaller ones due to the proportionally smaller impact of surface erosion on their total mass. Consequently, the choice of rock size and quality directly affects the long-term stability and effectiveness of coastal defense structures. Regular monitoring and appropriate design adjustments will account for the predicted degradation and ensure the durability of the armour stone over the structure's intended lifespan.

4.2.2. Steel

Despite its widespread use and strength, steel has a significant carbon footprint, contributing approximately 230 $kgCO_2/m^2$ according to the NMD. This is in line with the study conducted by Broekens et al. (2011), which stated the use of steel should be avoided to reduce the carbon footprint. Moreover, in marine environments, steel is highly prone to corrosion, necessitating frequent maintenance or larger thickness to allow for erosion. This issue is particularly critical for thin, vertical structures like sheet piles, which, although they reduce material volume, lack the mass and structural integrity needed to resist significant wave forces and ensure stability. Reducing the reliance on steel or finding greener alternatives could be great steps towards lowering the environmental impact of hydraulic engineering projects.

4.2.3. Traditional Concrete

Besides the use of mineral resources, concrete is one of the most used products in hydraulic engineering. The carbon dioxide emissions from the production of concrete is almost completely caused by the production of cement. One of the most common cement is Portland cement, which is used as a binder (Adesina, 2020). The carbon footprint of concrete strongly depends on the desired compressive strength and the amount of cement additives. Additionally, varying cement types in the mixtures can have a noticeable impact. Common cement types include a certain amount of Portland cement and blast furnace cement. These types are indicated by CEM I, when it includes almost 100% Portland cement, and CEM III/A en CEM III/B when the blast furnace cement content is 40% and 70%, respectively. Table 4.3 presents the impact of varying concrete composition on the embodied carbon. However, when the Portland cement content is low, carbonation significantly increases the porosity at the surface. With less than 25% Portland cement, this leads to a greatly reduced resistance (Vermeulen, n.d.).

Table 4.3: Impact of Concrete Composition per m^3 on Embodied Carbon (Valerie Diemel et al., 2019)

Concrete type	Specific Weight m^3	Embodied Carbon $kgCO_2/m^3$	Database
C30/37 CEM I	2336	423	NMD
C30/37 CEM III/B	2386	212	NMD
C30/37 CEM I (30% granulate)	2311	421	NMD
C30/37 CEM III/B (30% granulate)	2391	212	NMD
C35/45 CEM I	2331	469	NMD
C35/45 CEM III/B	2391	241	NMD
C35/45 CEM I (30% granulate)	2341	468	NMD
C35/45 CEM III/B (30% granulate)	2386	240	NMD

The data suggests that the type of cement used in concrete significantly affects the embodied carbon emissions per cubic meter. A comparison of carbon emissions demonstrates that choosing different types of cement can result in substantial variations. For example, switching from CEM I to CEM III/B cement in a C30/37 concrete mix can cut embodied carbon emissions from 423 $kgCO_2/m^3$ to 212 $kgCO_2/m^3$, as indicated by the NMD. Similarly, in a C35/45 mix, replacing CEM I with CEM III/B cement reduces the emissions from 469 $kgCO_2/m^3$ to 241 $kgCO_2/m^3$. Such a change in cement type can halve the carbon footprint of the material, which can be seen in Figure 4.1. Although using 30% recycled concrete granulate has no direct carbon emissions in acquiring raw materials (Lifecycle phase A1), it has a negligible effect on overall emissions due to the consistent amount of cement used regardless. Figure 4.1 illustrates the carbon emissions associated with rock and concrete across each lifecycle phase. Rock displays minimal emissions across all lifecycle phases, positioning it as environmentally favourable option with respect to concrete. This data visually reinforces the importance of material selection in sustainable construction practices, emphasizing that choices like preferring CEM III/B cement can have a substantial impact on the carbon footprint of construction materials. In the context of designing a carbon-neutral breakwater, this research will further reference the CEM III/B type of cement as a central component in traditional concrete.

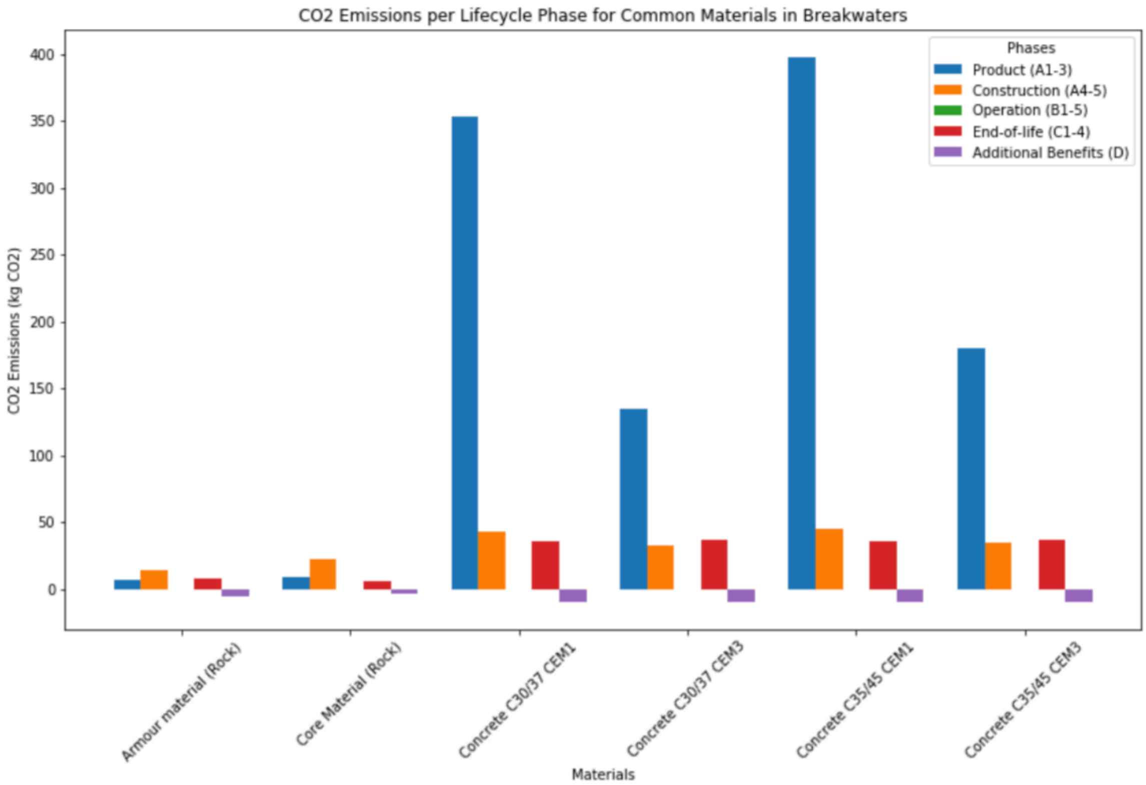


Figure 4.1: Carbon emissions associated with various commonly used materials distinguished per lifecycle phase

Conventional concrete mixtures vary in density, significantly affecting their performance in marine environments. According to Hudson (1953) and Van der Meer (1988), the stability of an armour unit increases with the submerged density of the concrete used. The provided plots in Figure 4.2 show stability numbers against carbon emissions for various concrete strengths across different significant wave heights. It offers a comprehensive view of the relationship between concrete composition and its performance in marine environments. Each subplot shows a different significant wave height, and each marker represents a different mixture with a different density, which can be seen in Table A.1. The varying colors indicate the different concrete strength classes.

The subplots of Figure 4.2 show that increasing the density of armour units definitely improves the stability. Examining normal density concrete mixtures, the subplots indicate that concrete with a strength category of C25/30 is associated with relatively lower carbon emissions, not exceeding 300 kg CO2/m^3. This suggests a potential for more sustainable application when lower concrete strength is sufficient. The data points within each strength category are spread out over a range of carbon emissions, indicating a diversity in the carbon footprint of different mixtures even within the same strength classification. There isn't a simple, direct relationship between carbon emissions and stability numbers within each strength category, implying the influence of additional factors on the stability number.

Interestingly, higher strength concretes, such as C40/50 and C50/60, show an overlap in carbon emissions with lower strength categories. This suggests that higher strength does not always correlate with higher emissions, indicating the possibility of achieving high-strength concrete without excessively increasing the environmental impact. However, the structural benefits of higher strengths are limited as well. Overall, the graph underscores the importance of balancing material strength, stability, and sustainability. Higher strength concrete does not necessarily mean a proportionally higher environmental impact, and optimizing concrete mixtures for both performance and environmental impact is key in coastal structures. The visualized data supports the need for an integrated approach to concrete selection, where structural requirements are met while minimizing the carbon footprint.

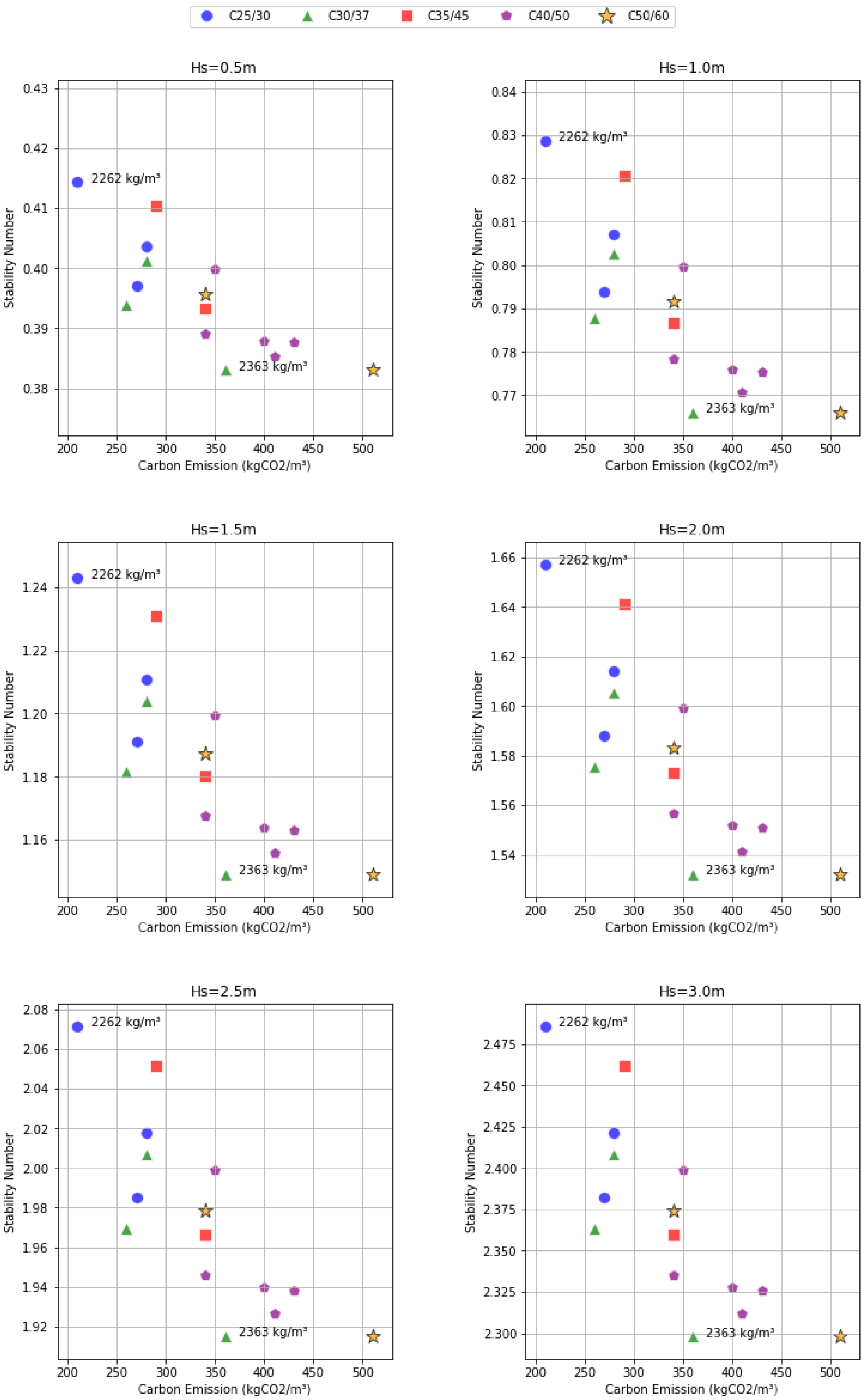


Figure 4.2: Stability Number vs Carbon Emission for varying significant wave height and concrete strength classes (Miller et al., 2015)

4.3. Recycled Materials

The use of recycled materials, such as concrete, in the construction of breakwaters offers a promising approach to enhancing sustainability and reducing environmental impact. Recycled rock and concrete, sourced from demolition debris through urban mining, can be repurposed to provide the necessary mass and stability for breakwater construction, reducing the demand for virgin materials and the associated carbon emissions from extraction and processing. One significant advantage is the environmental benefit of reusing materials that would otherwise contribute to waste, thereby decreasing the need for natural aggregate extraction and mitigating environmental impacts, with a reduction of 20% in carbon emissions (Bampanis and Vasilatos, 2023). Recycled concrete aggregates (RCA) can replace up to 25% of natural aggregates in concrete mixes without significantly compromising the strength and durability of the concrete. This substitution can lead to considerable reductions in carbon emissions and the overall carbon footprint of construction projects. However, recycled concrete has notable limitations. The presence of residual mortar on RCA particles increases water absorption and reduces the density and strength of the resulting concrete. This often necessitates higher cement content to achieve the desired strength levels, which can offset some environmental benefits. Additionally, RCA concrete can exhibit higher water uptake and lower resistance to chloride permeability and acid attack, affecting its long-term durability, especially in harsh marine environments. To overcome these challenges, careful mix design, proper treatment of RCA, and the use of admixtures can improve the performance of RCA concrete (Thomas et al., 2018).

Similarly, slag, the byproduct from the steel industry, offers significant potential as a recycled material for the construction of breakwaters, presenting both advantages and limitations. Its high grain density and shear strength contribute to the stability of rubble-mound marine structures (Krca et al., 2017). Utilizing steel slag can lead to substantial environmental and economic benefits by preventing the dumping of industrial by-products at landfills and reducing the need for virgin materials. Moreover, steel slag can be used as core material, which often requires a large volume. Consequently, significantly lowering the carbon emissions of breakwater construction by utilizing byproducts like steel slag. However, the material requires thorough aging and handling to ensure safety and performance, and its properties can vary depending on the production source, necessitating rigorous testing and quality control (Krca et al., 2017). The presence of fine particles in steel slag can reduce permeability and stability under hydrodynamic loading, making sieving and sorting essential. Additionally, any residual free lime or magnesium oxide must be managed to prevent environmental risks. Despite its demonstrated effectiveness in projects in the USA, the lack of universally defined standards for its use poses challenges for broader adoption. By addressing these limitations through proper processing and regulatory support, steel slag can be a valuable component in sustainable breakwater construction (Krca et al., 2017). It should be noted that currently, these byproducts do not contribute to carbon emissions since they are a by-product. However, new regulations will require these materials to be accounted for in carbon emissions, making them somewhat less favourable (Vermeulen, 2023).

4.4. Advanced Concrete Options

4.4.1. MagnaDense

MagnaDense is a high-density aggregate primarily composed of the mineral magnetite, mined in Sweden and widely used in the construction industry, particularly in the production of high-density concrete (See Interview B.5). This specialized aggregate contributes significantly to the increased density of concrete, reaching up to 3900 kg/m^3, and is utilized for its ability to enhance the stability of structures like breakwaters and coastal defenses. MagnaDense concrete enables the use of lower volume construction equipment and perform well in single top-layer configurations, providing a cost-effective alternative to traditional double layers. However, these units also present challenges, including increased placement complexity, higher sensitivity to progressive damage and filter material erosion, increased wave reflection and overtopping, and more handling movements during construction. Additionally, there are unresolved geotechnical concerns that necessitate further study to ensure comprehensive stability and performance (Van Gent et al., 2001).

Incorporating MagnaDense into concrete has the advantage to reduce material usage due to its high stability, which indirectly benefits the environment. However, MagnaDense products have a higher carbon footprint due to the necessity of transporting them over 2500 km to the Netherlands (Exterra b.v., 2006). This transportation involves mostly shipping and some trucking. To estimate the carbon footprint of MagnaDense products, the travel distance is added to the known carbon emissions of standard CEM III/B concrete, resulting in an approximate footprint of 600 $kgCO_2/m^3$, as per the National Material Database (NMD). Despite the increased carbon emissions associated with transporting MagnaDense from Sweden, the overall carbon footprint may be offset by the decreased volume of concrete required, thanks to its higher density. This reduction in material use, depending on the scale of the project, could lead to a potentially lower net CO_2 emission throughout the life-cycle of a construction project.

Moreover, the environmental considerations extend to the logistics of transporting MagnaDense, where efforts are made to minimize CO_2 emissions through efficient shipping methods. Although, the smaller scale shipments to specific regions like the Netherlands do raise the carbon footprint somewhat. Despite these challenges, the potential for reducing overall concrete volumes and the resultant decrease in total CO_2 emissions makes MagnaDense a compelling option for certain engineering applications, balancing performance with environmental sustainability.

Future Prospects To create a more sustainable and efficient product, research and development should focus on further reducing the carbon footprint associated with its transportation. This can be achieved by optimizing logistics, such as increasing the efficiency of shipping methods and exploring alternative, lower-emission transportation fuel options.

4.4.2. High-density geopolymer concrete

Traditional concrete, made from gravel aggregates and Portland cement can also include byproducts as steel furnace slag. However, this addition increases the chance of chemical reactions between the traditional Portland cement and the steel furnace slag, leading eventually to cracks. Geopolymer cement is an effective alternative to Portland cement, as it is made from industrial by-products, such as fly ash or slag, which does not happen to react with the steel furnace slag. Geopolymer can consist of many materials, as long as they are rich in silicon (Si) and aluminum (Al), which are used for the geopolymerisation process. So, the key difference lies in the chemical activation process. In traditional concrete, water reacts with Portland cement in a hydration reaction to form the hard, stone-like material we know as concrete. In geopolymer concrete, the fly ash and slag are mixed with an alkaline activator (often sodium or potassium silicate, combined with sodium or potassium hydroxide). This alkaline activator initiates a chemical reaction that leads to the polymerization of the Si and Al atoms in the source materials, forming a dense, hard, and durable matrix that binds the aggregates together (Appendix Interview B.1). A summary of the properties of geopolymer cement is given in Table 4.4.

Applicability Increasing the stability, could reduce the carbon footprint of the breakwater by replacing the large armour blocks by higher density armour units, leading to smaller layers (Van Gent et al., 2001). Recent studies, show development of high-density geopolymer concrete, consisting of 65% fly ash, 35% ground granulated blast furnace slag as the binder and steel furnace slag (SFS) as aggregates (Mahmood et al., 2020). This results in the use of lower volumes of material and zero cement. The material density was increased from 2300 kg/m^3 to 2630 kg/m^3, which led to a reduction of 43% in armour unit weight and will lead to a reduction in size, maintaining the structural stability of breakwaters (Mahmood et al., 2020). The applicability is very wide and the high-density geopolymer concrete armour units have shown a comparable performance to that of larger conventional armour units, meaning that they provide an opportunity to be used in response to the increasing wave energy on structures due to sea level rise (Howe and Cox, 2017, Appendix Interview B.1).

Local Availability Geopolymer concrete is made from industrial by-products and therefore widely available across the globe. India and China produce over 100 million tons/year of fly ash, USA around 75 million tons/year and various countries in Europe produce between the 2 to 40 million tons/year (Ghazali et al., 2019). In 2018, a total of 22.6 million tons of Steel furnace slag and 25.2 millions tons blast furnace slag was being produced in Europe. Local availability of these materials, minimize the carbon emissions associated with transport, which is a large contributor when using rock aggregates (Euroslag, 2022).

Limitations Although its a highly promising product for minimizing the carbon footprint of a breakwater, some limitations need to be noted. The compressive strength has not reached its full potential after 28 days, but keeps increasing until at least 90 days. This is due to the slow but continuous geopolymerisation, which is a complex phenomena (Oh et al., 2010). Although it often results in higher strength and more durable concrete, the additional time required and associated costs need to be considered. Additionally, the proportion of fly ash and slag needs to be preserved, as any change can impact the concretes behavior due to varieties in physio chemical properties (Foster, 2022). On top of that, the durability is being tested recently, consequently meaning that the durability is not proven yet. However, it is projected to be similar to traditional concrete, suggesting that geopolymer concrete can be considered a sustainable alternative (Foster, 2022).

Carbon Footprint The use of geopolymer cement has a significant effect on the total carbon emissions. According to a review on geopolymer cement by J. Davidovits, the use of geopolymer cement as an alternative to Portland cement results in a reduction of 70% of the carbon emissions of the lifecycle stages A1-3 when compared to CEM I (Davidovits, 2013) and 50% when compared CEM III (Interview B.1). The total reduction depends on the available industrial by-products. The total CO_2 emission of the production of geopolymer cement with slag as by product and with slag that needs to be manufactured is 0.208 tonne CO_2/tonne cement and 0.308 tonne CO_2/tonne cement respectively (Davidovits, 2013, Das et al., 2022). In other words, a reduction of 70-80% with comparison to the carbon dioxide emissions of Portland Cement (CEM 1) (1.02 CO_2/tonne).

Table 4.4: Summary of the properties of high-density geopolymer concrete

	Geopolymer concrete	
Carbon Footprint	136 $kgCO_2/m^3$	(Davidovits, 2013), (Das et al., 2022), (Interview B.1)
Applicability	In all weather conditions	(Mahmood et al., 2020), (Howe and Cox, 2017)
Local Availability	Worldwide availability	(Euroslag, 2022),(Ghazali et al., 2019)
Limitations	Sensitive to changes in mixtures	(Foster, 2022)
Durability	Similar to traditional concrete	(Foster, 2022)
Cost-effectiveness	€150/tonne €345/m^3	(Appendix Interview B.1)

Future Prospects Geopolymer concrete offers significant potential for sustainable construction, particularly in applications such as breakwaters. To maximize its potential, several key improvements are necessary. Achieving formal certification and establishing specific standards will facilitate its acceptance in the construction industry. Advancements in material composition, focusing on optimizing the use of industrial by-products like fly ash and slag, can enhance its strength and durability while maintaining low CO_2 emissions. Adapting to evolving regulations regarding the environmental impact of these by-products will also be of importance.

Additionally, developing efficient recycling processes will promote a circular economy, further boosting sustainability. Practical applications and pilot projects will provide valuable data, demonstrating the viability and benefits of geopolymer concrete. By addressing these areas, geopolymer concrete can become a leading material in sustainable construction, significantly reducing the sector's carbon footprint and contributing to the development of eco-friendly infrastructure.

However, the future demand for geopolymer concrete is limited by the fluctuating availability of key precursors like fly ash and blast furnace slag, environmental impact considerations, and the need for alternative raw materials. For instance, fly ash availability has been affected by energy transitions and changes in coal usage. Additionally, economic feasibility and scalability challenges, along with the need for clear regulatory frameworks, must be addressed to ensure its broader adoption and sustainability in construction (Verweij, 2022).

4.5. Alternative Material Solutions

This section shifts focus from traditional materials to alternatives. By exploring materials such as geotextile tubes, bamboo, brushwood, and timber, this section aims to indicate the potential of these resources to significantly reduce the carbon footprint of coastal defense structures. These alternatives not only promise sustainability but also offer opportunities to reduce concrete usage in breakwater construction.

4.5.1. New Application of Brushwood

Brushwood is often used in fascine mattresses, which are a common component of coastal engineering, particularly in the construction and stabilization of breakwaters. These mattresses are made of branches, or other fibrous materials, tightly bound and placed at seabed or riverbed to prevent the erosion of the soil. Their purpose is to provide structural stability to breakwaters. The strategic placement of fascine mattresses can significantly enhance the longevity and effectiveness of breakwaters, making them a cost-effective and environmentally friendly solution in coastal engineering projects. Their natural materials and construction technique allow for a minimally invasive approach that integrates well with the marine ecosystem, promoting sediment accumulation and even facilitating the growth of marine flora and fauna.

Applicability Fascine mattresses are particularly well-suited for use on a challenging subsoil, including soft, muddy substrates where they help compress and stabilize the sediment. They are also effective on sandy or loose sediments, reducing erosion and promoting sediment accumulation. Additionally, in erosion-prone areas, these mattresses shield the soil from water currents and wave action, minimizing erosion. Their flexibility makes them ideal for uneven and irregular topographies, as they can adapt to the contours of the ground, ensuring comprehensive coverage and enhancing the stability of structures like breakwaters. By means of a sinking-block one side of the mattress will be sunk towards the bed level, from which the rest of the mattress will be lowered with rubble stones.
Additionally, the willow branches can even be used as core material, by using local dredged material like peat to fill it up, and make it heavy. The production is similar to that of the fascine mattress, but the purpose is different. They contribute to the purpose of reducing intensity of wave action by dissipating the energy of incoming waves and trapping sediments, which strengthens the breakwater structure. They are especially useful in environments where underwater currents and wave forces are strong, providing a flexible yet durable barrier that adapts to underwater topography without compromising its protective functions. Also, it is a relatively lightweight structure which reduces the chance of settlement of the soil. Moreover, case studies have shown an applicability in water-depths of up to 3.75 meters in which it can withstand a wave height of up to 3 meters. Deeper could be possible, but requires larger foundation for stability (Bonhof, 2021). A similar application to consider is the concept of reed marshes or floating wetlands, which can be used in freshwater systems to attenuate waves and capture sediments. Deltares has conducted research on the wave damping effectiveness of these reed marshes, demonstrating their impact (Steeg and Wesenbeeck, 2011), although it is limited. The reed marshes function by trapping sludge through the reeds that grow on their surfaces, causing them to eventually sink and naturally integrate with the surrounding environment.

Local availability Fascine mattresses consist most of the time out of brushwood and natural fibers that are used for binding. The brushwood can be grown on local plantation, minimizing the carbon emissions associated with transport. When using the brushwood as core material, dredged material like peat can be locally achieved as it is available in abundance in The Netherlands. Dredging is often required to provide better navigable waterways and now it can be reused in new ways. Reed and corn cloths can be used to prevent the dredged material to be washed out through the branches. Additionally, rubble may be needed to sink the fascine mattresses.

Limitations A limitation of natural materials is the rate of degradation. Natural materials such as willow branches used in 'zinkstukken' decompose over time. This decomposition can vary widely based on environmental conditions such as water acidity, microbial activity, and climate. When wood is placed below the water surface, the material can last more than 40 years. However, when the natural materials like brushwood are placed at the water surface or above, they may start to significantly degrade after a couple of years, necessitating maintenance or replacement to ensure the integrity of the structure. Besides, the study conducted by Deltares concluded a limited wave transmission coefficient of 0.6 for waves (N=1000) larger than 0.4m and brushwood mattresses with a length of 4m. Incoming waves of

0.2m combined with mattresses of 12m in length show a transmission coefficient of around 0.3 (Steeg and Wesenbeeck, 2011). Depending on its application, this is something to take into account.

Carbon Footprint Van Aalsburg B.V. has done research on the carbon footprint of their own growing willow trees. According to the LCA, the carbon emissions related to the plantation of the willow branches is 0.106 tCO_2/t or 38.16 $kgCO_2/m^3$ (Ufkes, 2022). However, willow wood is capable of sequestering 23 tons of CO_2 per hectare. Each hectare has a yield of about 250 cubic meters per hectare, resulting in a carbon storage of 92 $kgCO_2/m^3$ (Bonhof, 2021). Consequently, the carbon footprint over the full life-cycle of using willow branches is -53.84 $kgCO_2/m^3$.

4.5.2. Sediment Blocks of dredged material

Sediment blocks from dredged material is a sustainable and innovative building material, developed from locally extracted dredge spoil, that offers an eco-friendly alternative to traditional materials such as concrete. The technology, which contributes to circularity and CO_2 reduction, produces strong, durable and weather-resistant building material through advanced processes. It is mainly used in hydraulic engineering projects, where, in addition to technical advantages, it offers ecological added value by promoting local biodiversity. Sediment blocks from dredged material marks a step forward towards more sustainable construction methods and the development of environmentally friendly infrastructure (Ekkelenkamp and Pieterse, 2023). A summary of the properties of geopolymer cement is given in Table 4.5.

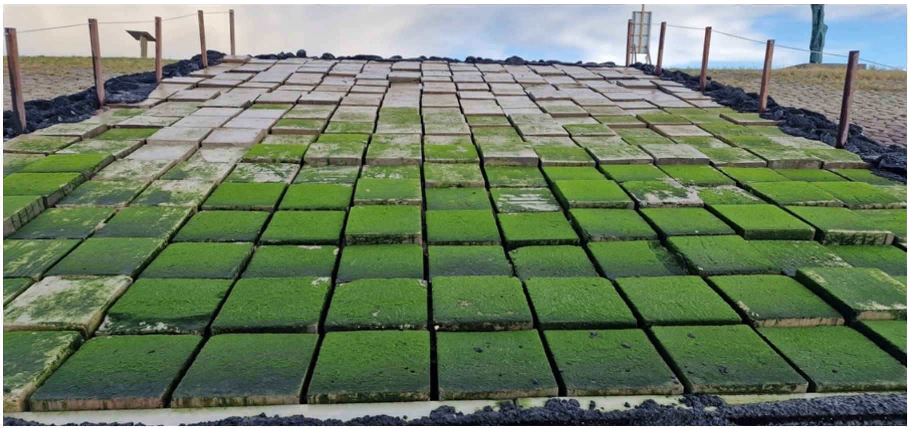


Figure 4.3: Blocks made from dredged material (Ekkelenkamp and Pieterse, 2023)

Applicability The sediment blocks consisting of dredged material offer high erosion resistance and compressive strength comparable to that of traditional concrete (C30/37) (Ekkelenkamp and Pieterse, 2023). These blocks are designed to withstand the impact of waves, which is essential for the stability and integrity of breakwater structures. However, the application of these sediment blocks is not yet tested in severe wave climates (Mooyaart, 2021). Since the properties of sediment blocks are similar to concrete, although behaving differently, their stability will be assumed to be as high as that of concrete units. Moreover, their natural materials and porous structure promote the growth of flora and provide shelters for fauna, creating new habitats that enhance the ecological value of the aquatic environment. The flexibility in the design of these foundation blocks allows adaptation to different wave environments and water depths, providing optimal stability and protection under various conditions. This adaptability supports flexible deployment for breakwater structures fit to the prevailing wave climate.

Local Availability The materials for the production of the sediment blocks from dredged material are derived from locally extracted dredged material, a by-product of the dredging process in waterways and harbours. This approach makes use of an otherwise often unused material, making the sediment blocks not only sustainable but also circular. The availability of dredged material varies by location, but given the ongoing need for dredging to keep waterways navigable, it represents a potentially rich source of material for its production. This local availability reduces transport costs and emissions, and supports the regional economy. Moreover, the use of local materials makes the sediment blocks ecologically beneficial by contributing to local biodiversity and integration within existing landscapes. As such, sediment blocks made from dredged material provide an excellent example of how local resources can be used efficiently and environmentally friendly in construction projects like breakwaters (Ekkelenkamp and Pieterse, 2023).

Limitations While these sediment blocks of dredged material offer many advantages in terms of sustainability and ecology, there are also some limitations to consider. One challenge is the variability in the quality and composition of dredged material, which depends on the location of extraction. This variability can affect the consistency and quality of the produced settling blocks. In addition, the production process of these sediment blocks requires specific technical expertise and specialised equipment for stabilising and pressing the dredged material, which can increase initial investment costs. There is also the need for extensive research and development to determine optimal formulations that follow the technical and environmental regulations. Although these sediment blocks offer ecological and circular benefits, there is an ongoing need for monitoring and evaluation to ensure their long-term performance and sustainability in different environmental conditions. Additionally, the sediment blocks take more than 56 days to reach their desired compressive strength of up to 30 MPa. This extra time needs to be taken into account. These constraints highlight the importance of continuous innovation and adaptation in the development of dredged sediment blocks (Koster and Ekkelenkamp, 2023). Furthermore, the production of a block requires special equipment, which is not largely available yet, limiting the production capacity and their applicability in large projects.

Carbon Footprint The carbon footprint of sediment blocks made from dredged material is significantly lower compared to traditional building materials such as concrete. This is due to the use of locally dredged material and the reduced use of cement. The production of these blocks uses dredged material, a residual product from waterway maintenance, reducing the need for mining new raw materials. This directly reduces the emissions associated with raw material extraction and transport. Moreover, the potentially lower need for cement, a material with high CO_2 emissions during production, similarly contributes to a reduction in the carbon footprint of the sediment blocks. However, there is room for further reducing the environmental impact of the production process. Continuous innovation could lower the carbon footprint of these sustainable materials, making sediment blocks from dredged material an even more attractive option for eco-friendly construction projects. Currently the production of a tonne sediment blocks, would be responsible for 100 kg of carbon dioxide emissions. Which is 30% lower than conventional concrete (Ekkelenkamp and Pieterse, 2023).

Table 4.5: Summary of the properties of sediment blocks from dredged material

Sediment Blocks of dredged material		
Aspect	**Value**	**Source**
Carbon Footprint	154 $kgCO_2/m^3$	(Ekkelenkamp and Pieterse, 2023)
Applicability	Moderate wave climate	(Mooyaart, 2021)
Local Availability	Available locally	(Ekkelenkamp and Pieterse, 2023)
Limitations	Takes long to reach high strength Sensitive mixtures	(Koster and Ekkelenkamp, 2023)
Durability	50 years	(Koster and Ekkelenkamp, 2023)
Costs-effectiveness	€300/tonne €71/tonne (future expectations)	(Ekkelenkamp and Pieterse, 2023)

Future Prospects For the implementation of the sediment blocks in the future, the right mixture is required. At this point, the development of optimized recipes such as the recipe, which combines 44% dredged sediment with 34% geopolymer binder, not only matches the compressive strength of traditional concrete but also maximizes the reuse of sediment. The dredged sediment primarily consists of a mix of clay, silt, sand, and organic materials, with the most suitable sample containing approximately 5.3% clay, 31.4% silt, 63.3% sand, and 6.2% organic matter (Ekkelenkamp and Pieterse, 2023). The low percentage of silt and organic matter makes it easier to stabilize, and its lower mineral oil content reduces the risk of chemical leaching. The substitution of CEM III for traditional cement in this mix shows significant potential in reducing CO_2 emissions. Embracing these innovative materials could offer a balance between mechanical stability and environmental sustainability. Future research and development in this area could further enhance these properties, creating the way for more efficient and eco-friendly construction solutions.

4.5.3. Geotextile Tube

A geotextile tube is a specialized construction material made from high-strength, woven geotextiles designed to contain dredged material. These tubes are often utilized in marine construction projects such as breakwaters, where they serve as the core structure, see Figure 4.4. Geotextile tubes can be stacked on top of each other to form a larger structure. The fabric of the geotextile allows water to pass through while securely holding the fill material, thereby maintaining the structural integrity of the tube. By using the geotextile tubes, the total amount of bulk materials needed for the rest of the structure can be significantly reduced (Yee et al., n.d.).

Figure 4.4: An application example of using a geotextile tube breakwater (Ocean Global, 2022)

Applicability A geotextile tube when filled, becomes suitable to provide for mass-gravity stability. Therefore, these geotextile tubes are known in many marine applications, such as: revetments, groynes, offshore breakwaters and the core of dykes and breakwaters. Geotextile tubes as breakwaters are often applied in relatively shallow water and, depending on the conditions to which it is exposed, additional techniques may be applied to increase the longevity of the structure. In the case of dictating wave forces, an armour layer of rocks can be placed on top of the geotextile tubes to protect it (Lawson, 2008).

Local Availability One of the major advantages of geotextile tubes is their ability to be filled with locally sourced materials, such as sand or other dredged substances. This not only makes them a practical option for many regions but also significantly cuts down on the transport costs and associated carbon emissions. By utilizing local fill materials, the overall resource requirements and environmental footprint of construction projects can be reduced significantly. Also, the geotextiles like polypropylene are available in abundance within a distance of 150 km (NMD).

Limitations Despite their benefits, geotextile tubes face certain limitations in terms of stability and durability. Technical evaluations reveal that these structures can be susceptible to both external and internal failure modes. External failures concern the entire structure's integrity, while internal failures focus on individual tubes. Key issues are shown in Appendix A and include sliding, overturning, bearing capacity, global stability, and foundation scour or settlement. Each of these factors must be carefully considered in the design and placement of geotextile tubes, especially in challenging environments. Geotextile tubes that are designed to be used in breakwaters, are exposed to hydraulic conditions varying from calm water to high waves and fast currents. The design and its functionality depends on the duration of the exposure to these hydraulic conditions. Generally geotextile tubes perform well in exposed conditions. However, in extreme weather conditions including persisting wave heights > 1.5 m and water currents > 1.5 m/s, additional protection is required in the form of rock armour (Lawson, 2008). The geotextile tube doesn't require rock armour in calmer climates, but it can still show some serviceability loss during its lifetime. The lifetime of a geotextile tube is often not more than 20 years (Interview B.3), which is relatively short for a breakwater but the geotextile tubes can reach a 100 year lifetime if properly protected (Interview B.2). Additionally, polypropylene slowly degrades over time, causing plastic particles to be released into the environment. This has a negative impact on the aquatic life (Bonhof, 2021).

Carbon Footprint The environmental impact of using geotextile tubes is notably lower compared to traditional construction materials like concrete. The emissions associated over the full lifetime of geotextile tubes is equal to 34.9 $kgCO_2/m^3$ according the Dutch Environmental Database, which is in a similar range to that of natural rock. Most of its associated carbon emissions are due to the transport to the site (A4) and the construction itself, including filling of the tube (A5). Additionally, geotextile tubes are not being recycled and need to be removed carefully. Consequently, the polypropylene needs to be extracted, transported and processed (C and D) having no additional benefits.

Future Prospects Prevention of the use polypropylene would improve the carbon footprint of the geotubes. Using biodegradable materials like jute instead, offers a promising new approach. This change brings multiple positive effects, such as preventing the release of microplastics into the environment. The carbon footprint is significantly reduced, as the end-of-life stages no longer play a large role. Incorporating jute in the LCA of geotubes would reduce the carbon footprint of a geotube to less than 6 $kgCO_2/m^3$. However, jute has a lifespan of only 5 to 10 years when covered, causing the dredged material to be released when its not consolidated enough. This lifespan becomes even shorter than 1 year, when directly exposed to waves. Similarly, jute is limited in its use as a geotextile tube material for larger diameters, due to its low tensile strength. This constraint leads to reduced durability and compromised structural integrity, making jute geotextile tubes more susceptible to damage and requiring frequent maintenance. To enhance jute's performance, various strategies can be employed: blending jute with synthetic fibers to create hybrid geotextiles, applying chemical treatments to strengthen the fibers, incorporating reinforcement grids, using advanced weaving techniques, and optimizing geometric designs. These improvements can significantly increase the tensile strength and durability of jute geotextile tubes, extending their application in environmental protection projects (Tanas et al., 2022).

Table 4.6: Overview of the advantages and limitations of geotextile tubes in marine environments

Geotextile Tube

Advantages	Limitations
Reduced transport distance	Suitable for shallow water
Ability of using local dredged material	Additional rock armour required during extreme weather conditions
Reduction in excavated rock volume	Settlement of the foundation needs to be minimalized
Simple equipment required for placement	Availability of local dredging materials
	Possible release of microplastics

Table 4.7: Summary of the properties of geotextile tubes (PP)

	Geotextile Tubes	
Aspect	**Value**	**Source**
Carbon Footprint	34.9 $kgCO_2/m^3$	(NMD Branco Schipper and Hövel, 2021)
Applicability	Applicable for wave height H_s<1.5m Tested for a 1000 waves	(Lawson, 2008), (Albers et al., 2013)
Local Availability	High	(Appendix Interview B.2)
Limitations	Not applicable for large depths Large circumference needed to reach larger height	(Albers et al., 2013)
Durability	10 years (exposed) 20 to 30 years 100 years (Unexposed)	(Appendix Interview B.2, InterviewB.3)
Cost-effectiveness	€300/meter €15/m^3	(Albers et al., 2013) (Appendix Interview B.2)

4.5.4. Timber

Timber is common used material world wide, which is known for its availability and eco-friendly aspect. It is often used by developing countries, due to its availability. Timber piles screens are considered to be protection elements that are used to protect the coast from erosion and could enhance sedimentation. Also, in the Dutch "kwelders", fences of wood have been used to stimulate the capture of sediment. The spacing between the installed wooden piles does not hinder sediment transport and exchange of (sea)water, resulting in an eco-friendly breakwater that harmonizes with the environment. In Table 4.8 the properties of timber are summarized. Moreover, the implementation of a timber pile screen or fence requires a relatively small amount of materials, indicating a promising solution.

Applicability Timber serves as a versatile material in wave dissipation structures, finding application in both fresh and saltwater environments. Its effectiveness in reducing wave heights depends on various factors including fence thickness, porosity, and relative freeboard, which is the distance between the water level and the top of the fence.

Timber structures used to attenuate waves, such as fences can be designed in multiple ways. Two common applications are timber piles placed in multiple rows without infill or including infill. Recent research has shown that the presence of infill significantly enhances wave attenuation, even with maximum porosity, increasing the proportion of wave-energy dissipation inside the fence. Lower infill porosity reduces transmitted wave height but enhances wave reflection, and thereby limiting wave energy dissipation inside the fence (Mai et al., 2020). Fences filled with brushwood, show efficient reduction of short wave heights while maintaining minimal impact on longer waves, as demonstrated by Dao et al. (Dao et al., 2018). This efficiency increases with a higher relative freeboard ratio, as observed in studies (Dao et al., 2022). Placing timber piles in shallow water increases the relative freeboard, thereby enhancing wave reduction due to increased pre-dissipation, particularly when situated near the shore or in shallow waters (Dao et al., 2022).

Research by Dao et al. (2021), highlights a significant relationship between fence thickness and wave transmission. The transmission coefficient, which indicates wave reduction, varies with the ratio of fence width to wave height. When this ratio is higher, the coefficient shows greater wave reduction. Conversely, a lower ratio results in less wave reduction. This difference is attributed to the timber fence's effectiveness in damping smaller waves more efficiently than larger waves (Dao et al., 2021).

The last parameter contributing to the dissipation of waves by the timber fence is its porosity. Mai et al. conducted a research on the relation between the transmission coefficient and the relative fence thickness for different types porosities. In this research, the wave height in front of the fence was compared to the wave height behind the fence with two fence thicknesses and two porosities of 50% and 90%. The fences show a maximum wave reduction of 72% for the case of the largest fence width with the lowest porosity (50%), whilst the fence with a porosity of 90% could only reach a maximum reduction of 29% (Mai et al., 2020).

Besides the parameters of the fence itself, the wave characteristics can significantly affect the wave dampening by the fence. A larger wave height reduces the wave transmission coefficient and increases the wave dissipation coefficient. On the other hand, the water depth and the wave period show opposite effects (Shu et al., 2023).

Local Availability Timber is often locally available, which minimizes the transportation costs and carbon footprint of the structure. Proper management of forest resources can ensure the preservation of timber resources and can make the application of wood a reliable and environmentally friendly option. The challenging part is the availability of the certain types of wood. In Europe timber softwood types like European oak and European redwood/whitewood are available, with a durability of max 15 and 10 years, respectively. European hardwood like Robinia has a durability of up to 25 years. However, the most durable types in the marine environment originate, according to the European standards, from South-America and Africa (Nen-En, 2016), and are therefore less available for the European countries, see Table 4.9.

Limitations The natural durability of timber refers to the resistance to biological attack. The resistance against this attack vary per environment and per timber type. According to the European standard (Nen-En, 2016) different types of timber can be classified in 5 groups, distinguished by their natural durability. Class 1 timber types, are proven to be very durable. Examples of class 1 timber types are heartwood such as Jarrah and Greenheart, which have a durability of over 25 years. These types originate from South-America or Africa. European hardwood types often do not have a natural durability higher than 25 years, as can be seen in Table 4.9, which limits their application. Consequently, this has effect on the amount of maintenance that has to be done, as well as the treatment that is required for the timber to withstand certain forces and biological attacks. Another limitation is the carbon storage in the forests that is being affected by the use of timber. According to the Food and Agriculture Organization of the United Nations the global carbon storage in forests has been decreasing by multiple gigatonnes since 1990 (FAO, 2020).

Carbon Footprint The utilisation of timber can have a significant impact on the reduction of the total carbon footprint. The carbon emissions associated with timber vary, depending on the wood type and the origin of the wood. For that reason it is important to distinguish the cradle-to-gate carbon emission value and the cradle-to-grave value. the cradle-to-grave value includes the transport contribution to the total carbon emissions, but takes into account the end-of-life value as well. The cradle-to-gate carbon emission associated with (tropical) hardwood lies in the range from 200 to 300 $kgCO_2/m^3$. However, the cradle-to-cradle value shows a different and lower value with a carbon emission for hardwood of 4 $kgCO_2/m^3$, due to the end-of-life contributions (van der Lugt and Vogtlander, 2015). This calculation includes the carbon sequestration of wood of 0.19 $kgCO_2/kg$ (van der Lugt and Vogtlander, 2015). Contrarily, according to the Dutch Environmental Database the carbon footprint of different wood types is much higher, as can be seen in Table 4.9. This can be explained by the omission of carbon sequestration in the available data.

Table 4.8: Summary of the properties of timber

Timber		
Aspect	**Value**	**Source**
Applicability	Pre-dissipation in shallow water enhances wave reduction Higher waves increase the transmission coefficient. Tested for wave height H_s<1.5m	(Mai et al., 2020), (Dao et al., 2018), (Dao et al., 2022), (Shu et al., 2023)
Local Availability	Softwood is locally available. Durable hardwood less available in Europe	(Nen-En, 2016)
Limitations	Timber durability varies Pre-treatment required Forest management required	(Nen-En, 2016)
Durability	Class 1 timber: >25 years European timber: max 25 years	(Nen-En, 2016)
Cost-effectiveness	€800/m^3	(Beijers, n.d.)

Table 4.9: Timber Types: Durability, Distance, and Cradle-to-Cradle Impact

Wood Type	**Durability (Years)**	**Distance (km)**	**Cradle-to-cradle (kg/m^3)**	Database
Hardwood South America	30+	10,000	223	NMD
Hardwood Africa	30+	7,000	283.5	NMD
Hardwood EU	25	1,000	211.5	NMD
Softwood EU	15	300	-334	NMD

4.5.5. Bamboo

Bamboo has a similar application as timber (see Figure 4.5). However, the long production time of timber has some downsides on the environmental impact with comparison to bamboo. Bamboo is nowadays being used in many different configurations and the demand is increasing. The use of bamboo reduces some stress on the existing forests as the demand shifts towards bamboo, which indirectly has a positive impact on the carbon sequestration by the forests. On grounds of the similar applicability as timber, this section is not going to elaborate further on that. The properties of bamboo are summarized in Table 4.10. Bamboo presents a range of benefits as a construction material. Its processing is straightforward, requiring minimal expertise and equipment, which results in a low initial investment. Despite its lightweight nature, bamboo is exceptionally strong, with a tensile strength higher than that of steel. Moreover, it demands far less energy for structural purposes compared to steel or concrete, providing it is a practical substitute for load-bearing tasks. The flexibility and fast growth rate of bamboo, coupled with its favourable weight-to-height ratio, offer abundant possibilities for construction projects. Furthermore, its hollow structure provides excellent structural integrity when compared to timber (Kaur, 2018).

Local Availability Bamboo is grass located in almost every continent on the globe and has a high growing speed. Giant bamboo species in tropical countries can grow up to 30 meters within six months, explaining their high availability (Pablo van der Lugt, 2008). When harvested, bamboo does not require replanting, because it is able to regenerate from its existing root system. Moso is a common bamboo specie which is largely available as construction material as it is able to grow in temperate regions. These species are also found in Italy, significantly reducing transport distances (Marchi et al., 2023).

Limitations Untreated, the lifespan of bamboo reaches not more than 3 years. The vulnerable shelf of the bamboo needs to be treated, to increase its lifespan. Additionally, present preservatives are often known to be environmentally unfriendly (Kaur, 2018). On top of that, due to its high space occupation, it is not efficient during transport.

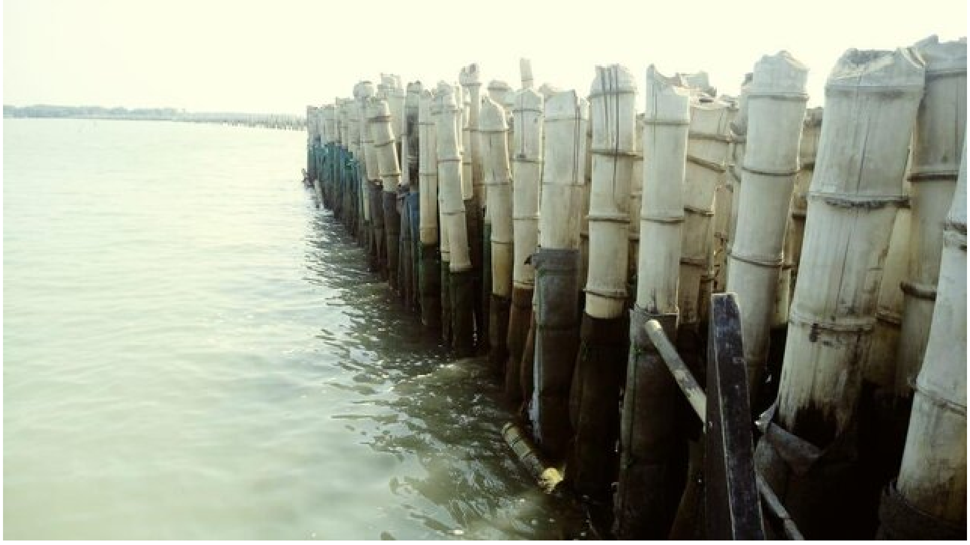


Figure 4.5: An application example of using a bamboo breakwater (Achiari et al., 2020)

Carbon Footprint Bamboo has the potential to achieve a negative carbon footprint over their full life cycle, even if the bamboo originating from Asia has to be transported to Europe, according to an environmental assessment done by Van der Lugt et al. (2015). This assessment takes into account complete life cycle of Chinese bamboo that is utilised in Rotterdam, including the carbon sequestration by bamboo. The cradle-to-gate (gate of a warehouse in Rotterdam) carbon footprint value for the production of a bamboo stem with its origin in China is 1.45 $kgCO_2$/kg stem. However, eliminating the overseas transport by using the bamboo stems in the local environment, reduces the cradle-to-gate value to 0.19 $kgCO_2$/kg stem. On the other hand, due to the extensive root system of bamboo, it has a larger carbon storing capability than wood. Resulting in a sequestered carbon value of 0.54 $kgCO_2$/kg. On top of that, bamboo in its end-of-life phase can be used for electricity production or Bio-energy, resulting in carbon dioxide credit of 0.70 $kgCO_2$/kg.(van der Lugt and Vogtlander, 2015).

Due to its low weight/volume ratio, the sea transport emission is higher, than for processed bamboo, resulting in a carbon footprint over the full life cycle of a bamboo stem of 0.21 $kgCO_2$/kg. This still indicates a large amount of carbon emissions, however the total amount required is significantly lower resulting in a lower total carbon footprint. When you compare it with Bamboo that is processed into an industrial product like a beam, made of compressed bamboo, the carbon footprint reaches a negative value of -0.380 $kgCO_2$/kg. The international sea transport contributes 15-25% to the total carbon footprint of using Chinese bamboo. Searching for a more local source, would significantly reduce the environmental impact (van der Lugt and Vogtlander, 2015). For the context of this research, unprocessed bamboo culms are used resulting in a smaller carbon footprint due to the processing which can be neglected. However, the eco-burden of sea transport will rise due to its low weight/volume ratio. Resulting in a larger carbon footprint. For simplicity, both processes of extra transport and the elimination of the processing of bamboo are assumed to outweigh each other. Consequently, bamboo culms having a carbon emission which is similar to that of a processed beam made out of bamboo.

Future Prospects Bamboo, known for its strength and versatility, presents significant potential for improving the sustainability of breakwaters. With proper selection of species, age, and preservative treatments, bamboo can achieve enhanced durability, making it a viable alternative to traditional materials. Treatments such as creosote, copper-chrome-arsenic (CCA), and heat treatments have been shown to extend the lifespan of bamboo from less than one year to 3-5 years when exposed to seawater (Wahab et al., 2009).

Secondly, standardizing these preservation techniques and making them widely accessible and harmless for the environment will be crucial. Developing cost-effective, scalable methods for treating bamboo will encourage broader adoption in construction. Thirdly, promoting awareness of bamboo's benefits (strength, low cost, environmental friendliness) among builders and policymakers can drive its acceptance as a viable alternative to traditional materials. Lastly, continuous monitoring and evaluation of

Table 4.10: Summary of the properties of bamboo

	Bamboo	
Aspect	**Value**	**Source**
Carbon Footprint	0.27 $kgCO_2/m^3$ (Cradle-To-Gate) -300 $kgCO_2/m^3$ (Cradle-To-Cradle)	(van der Lugt and Vogtlander, 2015)
Applicability	Pre-dissipation in shallow water enhances wave reduction Higher waves increase the transmission coefficient. Tested for wave height H_s<1.5m	(Mai et al., 2020), (Dao et al., 2018), (Dao et al., 2022), (Shu et al., 2023) (Albers et al., 2013)
Local Availability	Highly available due to fast growth rate Not available in every climate	(Pablo van der Lugt, 2008), (Marchi et al., 2023)
Limitations	Inefficient transport due to low weight/volume ratio Pre-treatment is required for longer lifespan	(Kaur, 2018)
Durability	1-3 years under wave conditions Up to 5 years with treatment	(Kaur, 2018), (Le Xuan et al., 2022), (Wahab et al.,
Costs-effectiveness	€300/m^3	(Van Der Lugt et al., 2006)

bamboo structures in real-world conditions will provide valuable data to refine and improve preservation practices further. By addressing these areas, bamboo can become a key player in sustainable construction, offering a more durable and eco-friendly solutions for various marine engineering applications.

4.5.6. Recycled HDPE

Recycling plastic is becoming a popular method in reducing the use of raw materials and to mitigate with global warming. Currently, recycled plastics are used to form various construction materials. But what could be the implementations in hydraulic engineering? The reuse of plastic could save a lot of waste products and the need for manufactured cement and aggregates, leading to a reduction of CO_2 emissions. On top of that, the recycling process of HDPE accounts for only 0.24 tonne CO_2/tonne of treated HDPE (Laird, 2022).

Figure 4.6: Recycled HDPE compressed into blocks (source: ByFusion)

Recently, research has been done on the use of recycled thermoplastics to make construction materials. According to research conducted by Prathik Kulkarni et al. in which bricks made of 100% High-Density polyethylene (HDPE) and were used, showed multiple advantages with respect to ordinary bricks (Kulkarni et al., 2022). The weight (density) of the bricks is lowered by 55%, while increasing the compressive strength by 14% with respect to the conventional brick. Yet, the density of HDPE is between 900 kg/m^3 and 1000 kg/m^3, meaning the bricks have a density lower or equal to that of water. Consequently, recycled HDPE used in this form could be suitable for floating breakwaters (e.g. box-type floating breakwater). Another advantage, is the minimal absorption of water, thus making them resistant against water leakage.

A different option is filling up hollow blocks made from recycled HDPE with locally dredged material and let it sink. The breakwater can be built up like a conventional rubble mound breakwater by using recycled HDPE as a core material. Eventually, avoiding the use of raw materials and concrete and minimizing the carbon footprint. The ByBlock, however, has its limitations in breakwater construction. The material is not designed to endure direct exposure to waves, wind, and saltwater without external protection such as weatherboard, stucco, or paneling (ByFusion Global, Inc., 2024). Without these coverings, ByBlock could suffer from UV radiation, weather, and environmental degradation, shortening its lifespan. Furthermore, with a density of about 900 kg/m^3, ByBlock is buoyant, presenting challenges for underwater placement since it will float rather than settle into the structure. This requires creative solutions such as using heavier materials like concrete to anchor ByBlock securely or applying weighted frames and ballast to stabilize it.

While known for its lightweight and insulating nature, ByBlock's manufacturing process, relying on steam and compression, can cause small pieces to break off under rough handling, which may impact its structural integrity in breakwaters and will affect the environment. This makes it no suitable material, and therefore it will not be further considered in the rest of this study. Despite its limitations, ByBlock can be used innovatively if its buoyancy and structural weaknesses are carefully managed, potentially in combination with other materials. Especially the prevention of environmental degradation is a requirement to be used in marine environments (ByFusion Global, Inc., 2024).

Future configurations could include encapsulating HDPE blocks with durable, non-toxic coatings to prevent plastic degradation and release into the environment. Possible materials for these coatings include marine-grade epoxy, polyurethane, or specialized plastic coatings that offer UV and weather resistance. Another approach is to combine HDPE blocks with traditional materials like concrete, using HDPE as a core and concrete as a protective outer layer. By exploring these configurations, the potential of recycled HDPE in marine construction can be maximized while mitigating environmental impacts.

4.6. Concluding Remarks

CO_2-neutral breakwaters, while technically promising, face several critical issues related to structural integrity, environmental impact, material limitations, and knowledge gaps. Traditional materials like concrete and rock are favoured for their proven durability and ability to withstand harsh marine environments. While minimizing material volume is an important consideration in achieving CO_2-neutral breakwaters, traditional materials like concrete and rock often require a large volume of materials to achieve the desired function. On the contrary, constructions like sheet piles, although advantageous for reducing material volume, face limitations in terms of structural integrity and environmental impact. Sheet piles, being relatively thin and vertical structures, would primarily reflect waves, causing increased turbulence and wave height on the seaward side, potentially leading to erosion and undesirable other issues.

Alternative materials such as geopolymer concrete, recycled HDPE, and geotextile tubes show potential but require further research and development to ensure their long-term durability and performance in marine conditions. For instance, geopolymer concrete achieves its full potential only after 90 days, and its long-term reliability is still being evaluated. Additionally, newer materials often need supplementary protective measures in extreme conditions, which complicates their use. Geotextile tubes, for example, may require rock armour to handle severe wave climates, adding to their complexity. On top of that, geotextiles are often not recommended due to the potential release of microplastics into the environment.

Natural materials also present significant concerns. Although materials like bamboo and timber have lower carbon footprints compared to conventional options, they have their drawbacks. Bamboo, despite its rapid growth and negative carbon footprint potential, needs treatment to prevent quick degradation in marine environments. Or require regular replacements to maintain structural integrity. Timber varies greatly in durability and typically requires pre-treatment, which can be environmentally harmful.

Moreover, the benefits of some materials can be canceled by transportation emissions. For instance, MagnaDense concrete has to potential to reduce material usage due to its high density, but it has a higher carbon footprint because it must be transported over long distances from Sweden to construction sites. Innovative materials also face constraints due to their developmental stages. Sediment blocks made from dredged material and high-density geopolymer concrete have limited applicability because of variability in material quality and the need for specialized production processes. These materials require extensive research and development to optimize formulations that meet technical and environmental standards.

The lack of long-term performance data for many materials complicates their use. Predicting the behaviour of these materials over the expected lifespan of breakwater structures is challenging without sufficient data. For instance, while there is significant interest in geopolymer concrete, more information on its long-term durability and performance in marine environments is necessary. Moreover, the impact of transport emissions needs to be studied. If transport emissions are minimized through the use of alternative fuels or more efficient transport methods, it is crucial to evaluate which materials would then be the most sustainable options.

In conclusion, achieving CO_2-neutral breakwaters is technically feasible, but several critical issues need to be addressed. These include ensuring the structural integrity and long-term performance of alternative materials, managing environmental impacts, overcoming material limitations, and addressing significant knowledge gaps through further research and development. These steps are necessary to realize the goal of CO_2-neutral breakwaters.

5 Applying the Civil Engineering Elementary Design Approach for Carbon Neutral Breakwaters

5.1. Introduction

In this chapter, a structured approach to design a carbon neutral breakwater is described. This methodology is based on the Civil Engineering Elementary Design Approach (Voorendt, 2015) and includes new techniques within the steps to incorporate carbon neutrality into design projects. Each step in the flowchart, depicted in Figure 5.1, is described in a dedicated section of the chapter, detailing the steps from initial system analysis to the final actual design. These steps are followed with some additional requirements and are tested with data by means of a case study in the next chapter. This methodology involves additional steps focused on carbon neutrality, indicated in green, whereas a general breakwater design primarily focuses on stability and strength. Furthermore, the flowchart includes feedback loops, which are crucial at this stage since carbon neutrality in breakwaters is still an emerging field and not yet established knowledge.

Step 1: System Analysis - Section 5.2 lays the groundwork by examining the existing system or situation that needs addressing, identifying key factors on which the design is based, such as the boundary conditions, like the subsoil data, the wind data and the hydraulic conditions. This step is similar to a general design approach.

Step 2: Defining Requirements - Section 5.3 delves into the requirements associated with the construction of carbon neutral breakwaters. This is where the design approach starts to differ from the general design approach. The development of these requirements is influenced by the need to address both traditional engineering goals and the emerging focus on sustainability. The inclusion of environmental considerations ensures that the project not only meets functional objectives but also aligns with global sustainability goals, such as reducing carbon emissions and minimizing ecological impact.

Step 3: Defining Evaluation Criteria - Section 5.4 discusses how the criteria for evaluating potential solutions can be shaped by the presence of carbon neutrality as either a foundational requirement or as an evaluating criterion (represented by a dotted line). The criteria are developed by considering the entire life cycle of the materials and the construction process, ensuring an integrated assessment of environmental impact. This helps in prioritizing solutions that are sustainable in the long term.

Step 4: Development of Alternatives - Section 5.5, describes the process of developing alternatives, which is a standard engineering practice, but this methodology places a special emphasis on exploring materials and designs that contribute to carbon neutrality. The alternatives are generated based on innovative approaches and new technologies in sustainable construction. The exploration of alternative solutions helps finding the best possible design that meets all requirements, including those related to sustainability. This step encourages creativity and innovation, particularly in the selection of materials that have a lower carbon footprint.

Step 5: Verification of the alternatives - Section 5.6 verifies that all alternatives are feasible and meet both the functional, structural and environmental requirements. It involves confirming that the designs can withstand the expected loads and conditions while also being sustainable. Additional verification is done to assess the environmental impact of each alternative, particularly focusing on carbon emissions. This step also includes a feedback loop to reconsider the requirements if none of the alternatives meet the initial set requirements.

Step 6: Evaluation of the Alternatives - In Section 5.7, the evaluation process utilizes a multi-criteria analysis (MCA), specifically adapted to include criteria related to carbon neutrality, such as life-cycle emissions and resource efficiency. Each alternative is evaluated to ensure it meets the objectives established in the earlier steps. This process facilitates informed decision-making, aligning with the project's overarching goal of achieving carbon neutrality.

Step 7: Actual Design - The final phase of the process is described in Section 5.8. This section describes how the selected alternative is refined into the final design. It focuses on practical implementation, ensuring that the design sticks to the principles of carbon neutrality established at the beginning. When the (preliminary) design is established, the total carbon footprint of the construction is calculated, by means of the available tools, to indicate the potential of the design. When the carbon footprint of the actual design is higher than 0 $kgC0_2$, designs in alternative situations with different requirements and boundary conditions will be further elaborated to see the sensitivity of certain requirements.

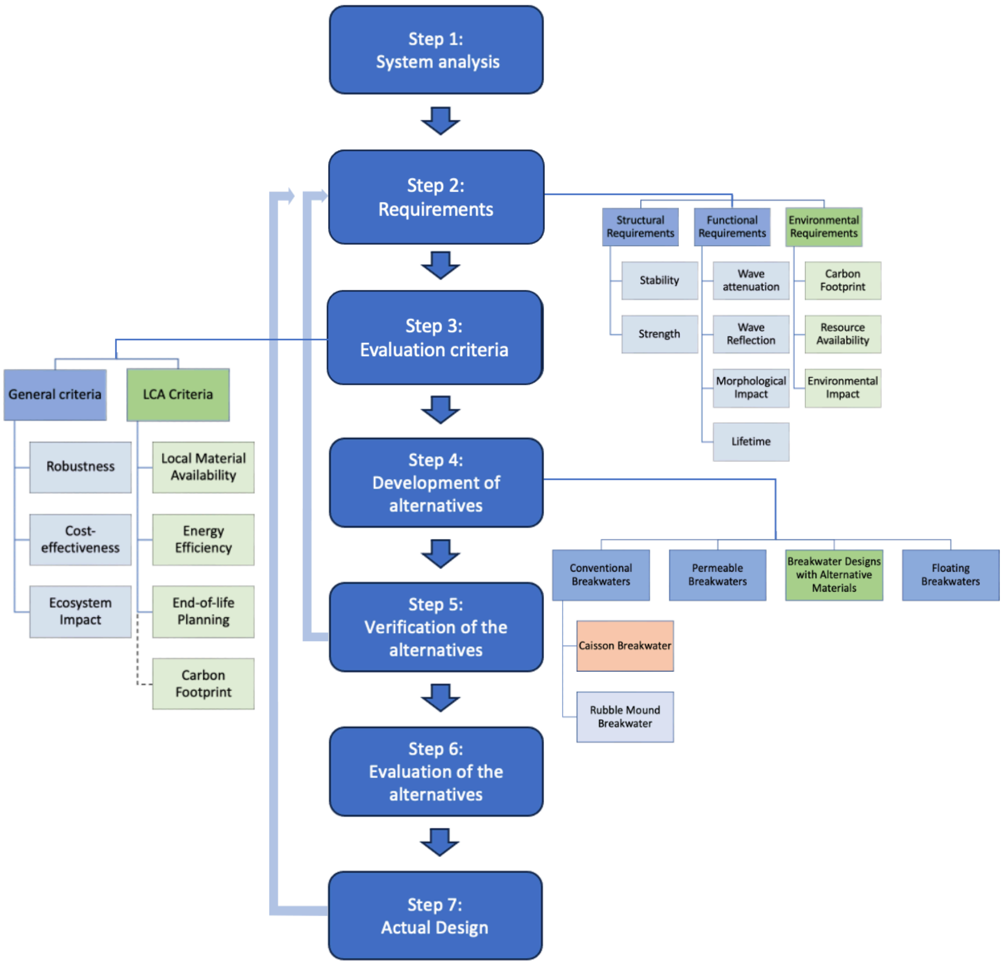


Figure 5.1: Systematic approach of designing a carbon neutral breakwater

This structured approach not only ensures that carbon neutrality is embedded in the design process but also illustrates the adaptability in application, whether as a primary requirement or as part of a broader evaluative framework. The flowchart serves as a visual guide through each stage, ensuring clarity and cohesion in understanding how carbon neutrality can be effectively integrated into engineering design methodologies. However, it must be noted that nowadays the current standard framework is not sufficient to design a carbon neutral breakwater. Research on data gaps and on new design methodologies must happen simultaneously in this approach. This combined effort will help in achieving carbon neutrality in breakwaters effectively.

5.2. System Analysis

Investigating the boundary conditions is a critical step in the system analysis phase of designing a (carbon-neutral) breakwater. Understanding the local environmental conditions such as wave heights, subsoil characteristics, and weather patterns help ensuring the structural integrity and effectiveness of the breakwater. Such boundary conditions determine if certain materials can be applied or not.

Understanding the hydraulic loads is required for ensuring the structural integrity of a breakwater. This knowledge allows engineers to calculate the structural loads and dynamic forces the breakwater must withstand to remain stable and functional over its lifespan. Accurate data on these marine conditions also enables the design of safety features and operational protocols that minimize risks to construction crews, maintenance personnel, and marine traffic. Moreover, it helps optimize the breakwater's orientation, length, and curvature, effectively dissipating wave energy to reduce coastal erosion and protect hinterland areas.

The characteristics of the subsoil are needed for determining the appropriate foundation for the breakwater. Different soil types, whether sand, clay, or rock, each with their unique properties such as permeability, compressibility, and shear strength, dictate specific foundation solutions to ensure stability and prevent differential settlement. Understanding these conditions, helps choosing the most cost-effective construction techniques and materials, impacting the overall project budget significantly. Proper planning based on accurate geotechnical data not only ensures a durable structure but also minimizes maintenance costs over time, a significant advantage given the harsh conditions faced by breakwaters.

Furthermore, conducting a thorough process and function analysis is the basis of the design. This analysis delves into how the breakwater will function within the existing systems. It helps to define the operational parameters of the breakwater, such as its capacity to withstand extreme weather events and its role in coastal management. By thoroughly understanding these functional aspects, engineers can design a breakwater that not only protects the coastline but also complements and enhances the area's ecological and socio-economic environment, aligning with the goal of carbon neutrality.

5.3. Defining Requirements

Setting requirements for the design relies on a thorough understanding of the system. This step establishes the foundation for the entire project by defining its goals and constraints. Similar to the general approach, it involves identifying the project's objectives. However, in this case, environmental requirements are considered alongside structural and functional needs. The boundary conditions and starting points established during the system analysis are incorporated into the requirements. These elements serve as a framework to determine the suitability of materials, helping to eliminate options that do not meet the necessary requirements from the beginning.

This step functions by integrating standards for performance, safety, and environmental impact into the design criteria. These requirements guide the development of a breakwater from its initial concept through to its construction and operation. By addressing these aspects early in the process, the project is designed to meet expected standards for durability, safety, and environmental management, ensuring a well-rounded and responsible approach.

There are various types of requirements depending on the system in which they are applied. The requirements for evaluating design alternatives are defined below. If a design alternative fails to meet these requirements, it must be revised or rejected. Figure 5.2 illustrates the process of defining these requirements. Since achieving carbon neutrality is the primary objective, environmental requirements are as significant as structural and functional ones. Environmental requirements in the carbon-neutral design approach ensure that the construction of breakwaters has minimal negative impact on the ecosystem and climate. By prioritizing emission reductions, using sustainable materials, and protecting local biodiversity, these requirements help create structures that align with global sustainability goals and minimize long-term environmental damage. While environmental considerations are typically viewed as criteria, they are integral to the design of a carbon-neutral breakwater and are therefore highlighted in green.

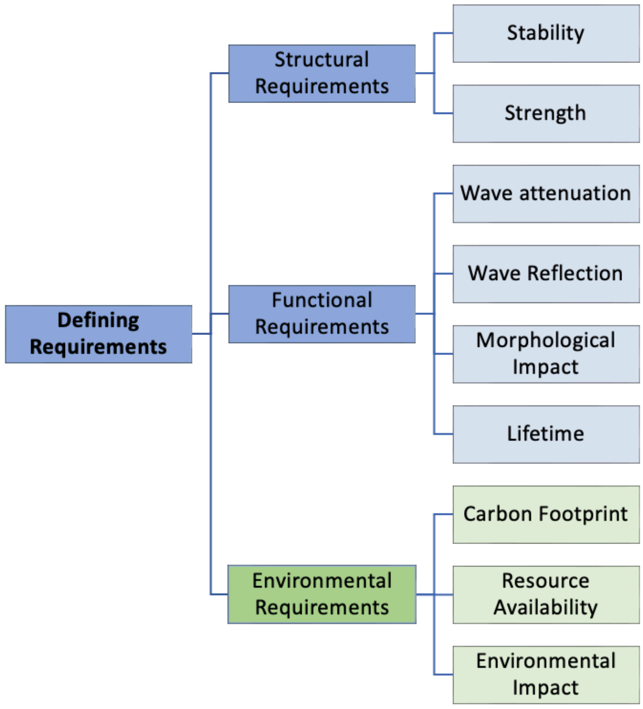


Figure 5.2: Intermediate steps when defining the requirements

- **Structural Requirements**
  - Stability: Breakwaters must withstand the physical forces of waves, currents, and tides.
  - Strength: Materials used must endure harsh marine environments, resisting weathering, corrosion, and biological degradation.
- **Environmental Requirements**
  - Environmental Impact: Designs should minimize negative impacts on the environment. This can include using environmentally friendly materials or designs that do not release toxic substances (e.g. microplastics) into the environment.
  - Carbon Footprint: Consideration of the materials life cycle and construction methods that minimize carbon emissions.
  - Resource Availability: Availability of (local) materials and construction capabilities can influence design choices and carbon emissions. Choosing for a sustainable alternative material, must not be a limiting factor in the construction process due to availability.
- **Functional Requirements**
  - Wave Attenuation: The reduction of wave energy to create a calm environment.
  - Wave Reflection: The management of wave reflection to prevent increased erosion along adjacent shorelines.
  - Sediment Transport: The maintenance or modification of natural sedimentary processes to prevent coastal erosion or to support beach nourishment efforts.
  - Lifetime: Breakwaters are designed for longevity, emphasizing the durability of materials and effective maintenance strategies to ensure the structure remains functional over an extended period, thereby minimizing carbon emissions related to maintenance activities.

Besides these requirements, every breakwater project has its own specific functional requirements. In breakwater design, requirements such as wave attenuation, wave reflection, and sediment transport are highly specific and vary depending on each project's local environmental conditions, its primary goals, and the geographical and ecological features of the area. For instance, a breakwater intended to create a calm harbour environment would prioritize wave attenuation to ensure safe mooring and operation of vessels. Conversely, in a project designed to enhance a recreational beach, managing wave reflection might be critical to avoid increasing erosion along adjacent shorelines. Sediment transport considerations play a large role in locations where natural sedimentary processes need to be maintained or modified to prevent coastal erosion or to support beach nourishment efforts. These specific requirements are shortly addressed as part of the general methodology discussed here, as our focus is on establishing a foundational design approach applicable across various contexts. This general methodology serves as a framework, which is then adapted to incorporate detailed, project-specific environmental and functional requirements, ensuring each project is tailored to meet its unique challenges and objectives. It should be noted that not all functional requirements are mentioned here. While functional requirements like wave overtopping and accessibility are important and should not be overlooked, they may be of significance in certain contexts. For example, wave overtopping might be a key concern in areas prone to severe storms, whereas accessibility could be a factor in projects emphasizing ease of maintenance or public use.

5.4. Defining Evaluating Criteria

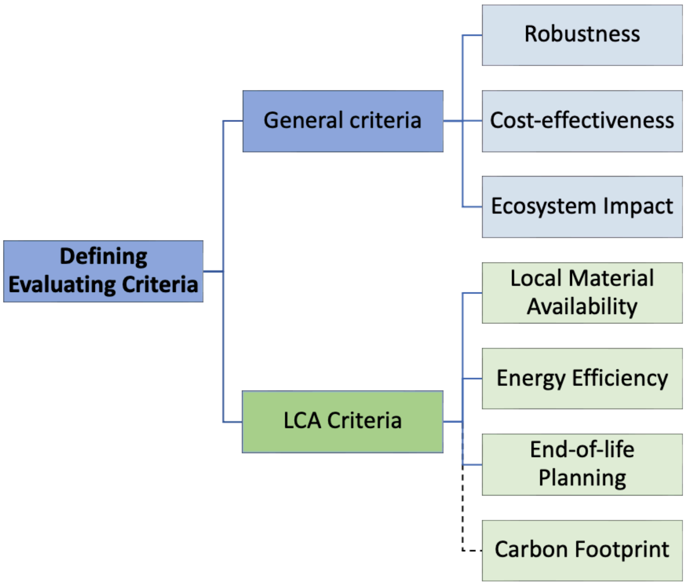


Figure 5.3: Intermediate steps when defining the evaluating criteria

Evaluation criteria help comparing different design alternatives in a project and are derived primarily from client desires, which often include non-quantifiable values. These criteria also include more technical aspects like maintainability and the potential disturbances caused by construction activities. The criteria below, used to evaluate the verified alternatives, are based on the stakeholder interests. Additionally, the evaluation criteria are more focused on the life-cycle analysis, due to the aim of achieving carbon neutrality. In Figure 5.3, the LCA criteria are highlighted in green.

- **Ecosystem Impact:** Assesses the breakwater's ability to mitigate the impact of currents that can cause erosion and affect sediment transport. Important for long-term shoreline stability.
- **Cost-effectiveness:** Represents the total financial investment required for the construction, maintenance, and potential future modifications of the breakwater. Cost-effectiveness is essential for budgetary considerations.
- **Local Availability of Materials:** Evaluates the distance materials must be transported to the construction site, which impacts the overall carbon emissions. Shorter transport distances are preferable for reducing the carbon footprint.
- **Energy Efficiency:** The energy required for the construction and maintenance of the breakwater should be minimized, and renewable energy sources should be used wherever possible.
- **End-of-Life Planning:** Consideration of how the breakwater will be decommissioned and the materials disposed of or reused at the end of its life is important for maintaining carbon neutrality. Although, breakwaters are built as a permanent structure and will rather be upgraded than demolished, in some cases when functions of breakwaters change over time, this could become an important factor. For that reason, this criteria is included, but has a small weight.

- **Robustness:** The robustness of the breakwater is a crucial criterion that influences the required maintenance. It refers to the structure's ability to withstand extreme conditions and unexpected events without failure. Using biodegradable materials, which degrade within a few years, compromises robustness because they necessitate frequent replacement, thereby may reduce overall sustainability.
- **Carbon Footprint:** Measures the breakwater's design and construction materials in minimizing carbon dioxide emissions, aligning with goals for carbon neutrality.
  Note: only considered when the carbon footprint is no requirement, but incorporated as evaluating criterion.

5.5. Development of Breakwater Design Concepts

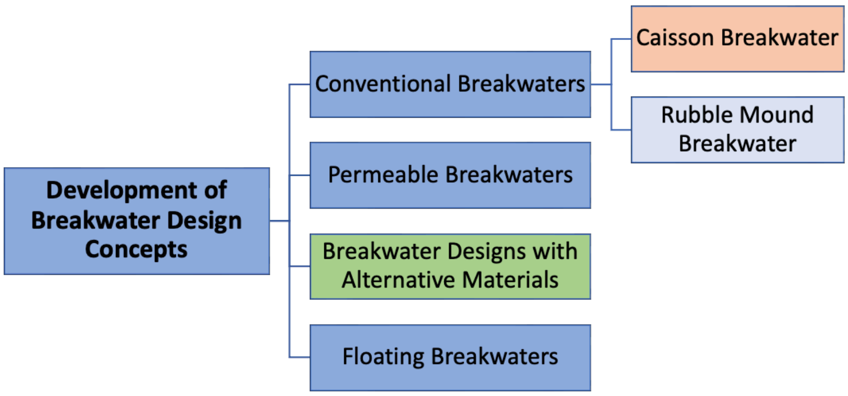


Figure 5.4: Intermediate steps when developing breakwater design concepts

The development of breakwater design concepts, as depicted in Figure 5.4, is a foundational stage in the planning process. This phase involves identifying and differentiating between various breakwater types, including both conventional and innovative approaches, applicable to both submerged and emerged structures. The purpose of this step is to explore and outline potential design options that align with the project's goals, particularly in terms of achieving carbon neutrality. It does not involve verification of the designs at this stage; rather, it focuses on indicating possible and potential design types concerning the materials used. However, vertical breakwater designs using caissons are initially avoided due to their reliance on large amounts of concrete.

For instance, caisson-type breakwaters, which typically require large amounts of concrete, are excluded due to their substantial carbon footprint. As highlighted in the study by Broekens et al. (2011), conventional rubble mound breakwaters present a more environmentally friendly alternative due to their lower carbon emissions. Therefore, caisson breakwaters are marked in red, indicating they are not viable options for a carbon-neutral approach. In contrast, conventional rubble mound breakwaters, which can incorporate materials like blast furnace slag in their core, offer various configurations that can further reduce carbon emissions.
Moreover, this phase also includes the exploration of innovative breakwater designs using both traditional and novel materials, highlighted in green. By identifying these potential designs, this step sets the groundwork for subsequent verification and refinement, aiming to develop solutions that are both functional and environmentally sustainable.

5.6. Verification of Alternatives

In the verification of breakwater design alternatives, key requirements such as stability, carbon footprint, strength, and material availability are evaluated to ensure the chosen design meets the necessary performance, safety, and environmental standards for its intended use. The visual tools provided help identify and eliminate unsuitable designs by clearly illustrating how each alternative meets these requirements. In other words, these figures act as verification tools within the case study, offering a structured framework for assessing and confirming the suitability of the breakwater designs. This framework supports informed decision-making, ensuring that the alternatives align with the project's goals of performance, safety, and sustainability.

It should be noted, that the data presented in the figures are based on currently available information and should not be taken as absolute truth. They provide an indication of the potential outcomes, and as new data becomes available, the graphs may change accordingly.

5.6.1. Hydraulic loads

The first requirement a breakwater needs to meet is to resist a certain load exerted on the structure by the waves. Figure 5.5, presents an analysis of breakwater designs in terms of their maximum wave height resistance and associated carbon emissions, which will be used as a verification tool in the case study.

Initially, the carbon emissions associated with the materials are calculated using current data from the National Material Database (NMD), which includes emissions from transportation and construction equipment, primarily powered by diesel. However, not all materials are included in the NMD, and their emissions data are sourced from existing literature (blue line). The analysis also explores a potential future scenario where transport facilities transition to being fully powered by green hydrogen and electricity, reflecting possible advancements in sustainable transportation (orange line). For geopolymer concrete, emissions are assumed to remain relatively stable, as reductions in transport emissions are offset by emissions from residual products like blast-furnace slag. This aspect is expected to be addressed more accurately as additional data becomes available (see Section 4.3).

However, some materials (e.g. bamboo) lack comprehensive data in the NMD. As a result, for these materials the analysis does not include an additional scenario where transport emissions are entirely excluded, meaning their calculated emissions may not fully account for future changes in transportation technology. Additionally, some materials (e.g. sediment blocks) involve minimal transport, resulting in negligible differences in emissions.
The key elements of the graph are summarized below:

- Solid Blue Bars: Represent the maximum wave height (in meters) that each design can withstand, based on literature studies in which physical tests were performed.
- Red Line: Illustrates the current carbon emissions associated with each breakwater design, indicating the present carbon footprint.
- Orange Line: Projects future carbon emission reductions, reflecting advancements in technology and materials that could lower the environmental impact.
- Green Dashed Line: Marks the zero carbon emission threshold. Materials below this line, such as bamboo and brushwood mattress, exhibit negative carbon emissions, meaning they sequester more CO_2 than they emit, highlighting their potential for sustainable applications.

This comprehensive evaluation ensures that each breakwater design is assessed not only for its structural integrity but also for its environmental sustainability, aligning with the overall goal of achieving carbon neutrality.

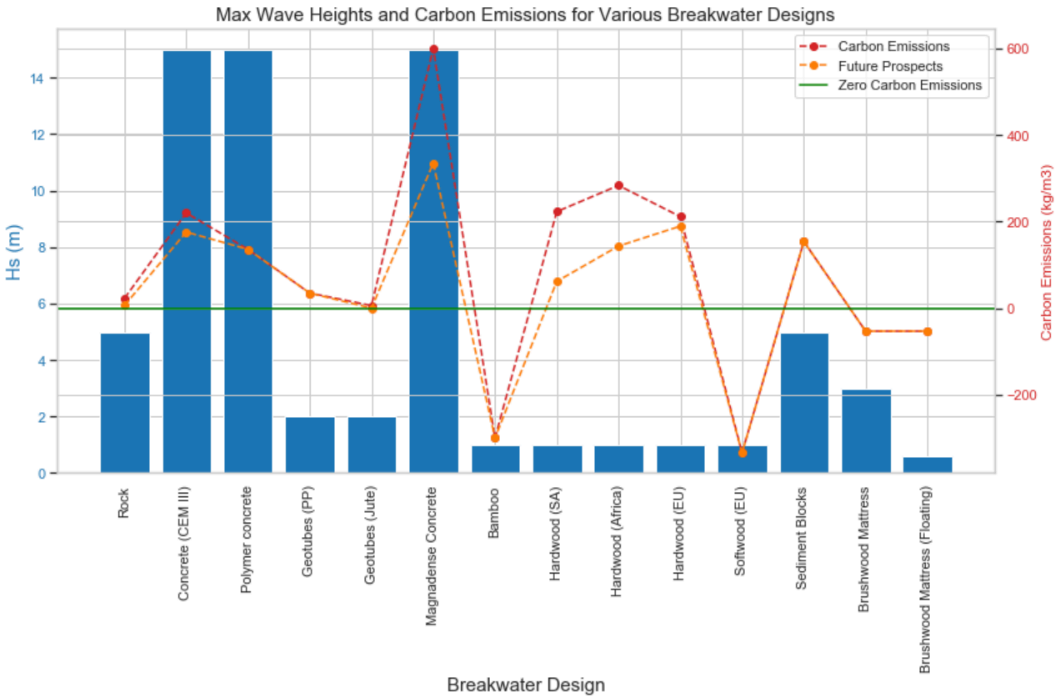


Figure 5.5: The wave height resistance of materials and their associated carbon emissions over their full life-time

5.6.2. Strength

The second requirement is the strength of the design, which ensures the long-term effectiveness and the durability of breakwaters, reducing the need for frequent repairs and replacements, and thereby minimizing environmental and economic impacts. Figure 5.6 illustrates the relationship between the durability of different breakwater construction materials and their associated cradle-to-cradle carbon emissions (in kg/m^3). This comparison provides clear insights into both the longevity and sustainability of each material, allowing for an informed evaluation of their overall environmental impact. For the materials, the key elements of the graph are described as follows:

- Blue Bars: These bars represent the range of durability for each material, indicating how long each material is expected to last when used in breakwater construction.
- Red Vertical Bars: These bars depict the potential future reduction in carbon emissions for some materials. The reductions are based on possible improvements such as minimizing transport emissions through the use of electric vehicles and equipment, or the use of recycled materials in the case of concrete.
- Orange Bar: Unique to rock, this bar represents the sensitivity analysis using either DuboCalc (NMD) or SimaPro (EcoInvent) tools. It provides an understanding of the environmental impact assessment variations based on different calculation methods.

The graph includes several additional markers for clarity:

- Set A2, represented by the gray dashed line, calculates the carbon footprint of hardwood using the new calculation method, which incorporates carbon sequestration. This results in a significantly negative carbon footprint. However, this data is not yet available or up-to-date.
- The 50 Years Threshold, shown by the vertical solid orange line, marks durability benchmark for the materials.
- The horizontal solid green line indicates zero carbon emissions, serving as a reference for evaluating each material's sustainability.

Each material's position on the graph visually represents its trade-off between durability and carbon emissions, assisting in the selection of the most suitable and sustainable material for breakwater construction.

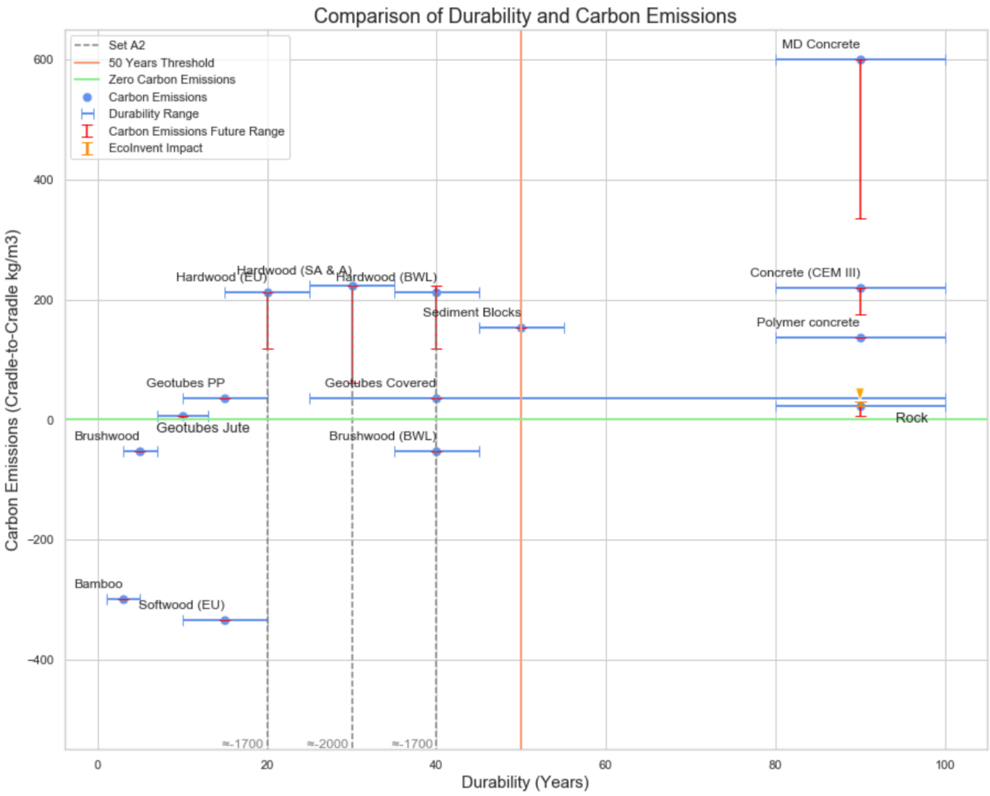


Figure 5.6: The lifetime of materials versus the carbon emissions

5.6.3. Availability

The provided Figure 5.7, offers an insightful view into the availability of various materials used in breakwater construction, categorized by distance the materials need to be transported from. The length of breakwaters can range from tens of meters to a few kilometers, like the breakwaters at the port of IJmuiden (Bosboom and Stive, 2021). A breakwater up to 500 meters in length is considered short in this research, while one longer than 2000 meters in length is considered long. The graph categorizes breakwater lengths into three ranges:

- 0-500 m (Short)
- 500-2000 m (Medium)
- 2000+ m (Long)

In addition, the transport distances from cradle to site of the material are represented by different shades of blue: light blue for up to 200 km, medium blue for up to 2000 km, and dark blue for 2000 km and beyond. Additionally, the sky blue bar indicate the future prospect for sediment blocks.

The analysis underscores the importance of considering local material availability in the planning and design of sustainable breakwater projects. It highlights the need for strategic sourcing of materials like sediment blocks, which, while sustainable, may have limited production capacity. Understanding these dynamics is crucial for optimizing logistics, reducing costs, and minimizing the environmental impact of transportation. This comprehensive approach ensures that the most appropriate and sustainable materials are chosen based on their availability and the distances they need to be transported, ultimately contributing to the overall sustainability and efficiency of breakwater construction projects.

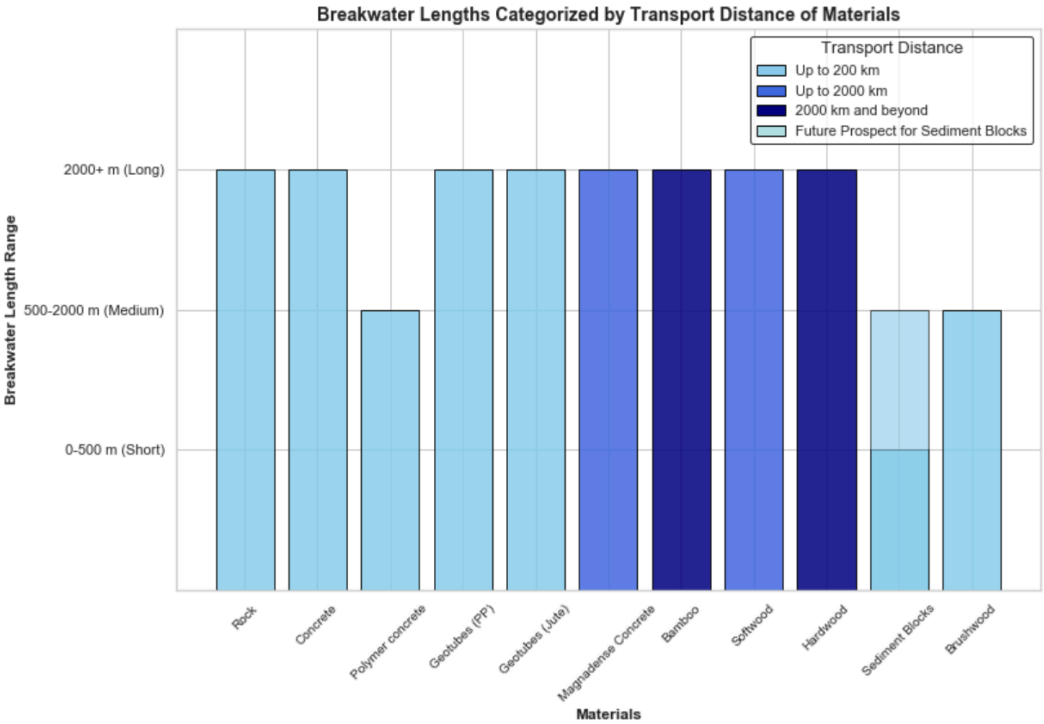


Figure 5.7: The overall availability of the materials and their local availability

5.6.4. Water depth

Figure 5.8, illustrates the applicable water depth ranges for several breakwater materials, providing a visual representation of each material's suitability. The figure emphasizes the importance of selecting appropriate materials based on the specific water depth and environmental conditions. This approach ensures optimal performance and longevity of the breakwater structures, tailored to the unique requirements of each projects location. Understanding the depth suitability of each material assists in making informed decisions for the construction and maintenance of effective and sustainable breakwater systems.

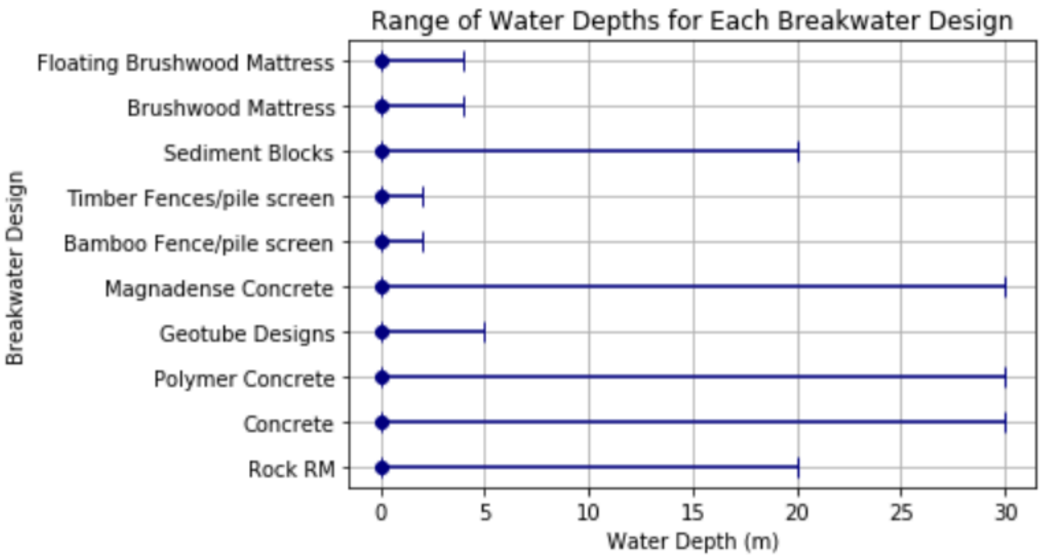
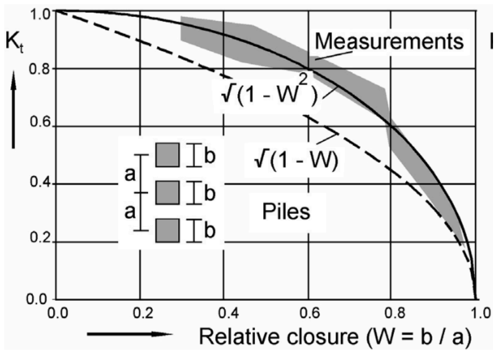


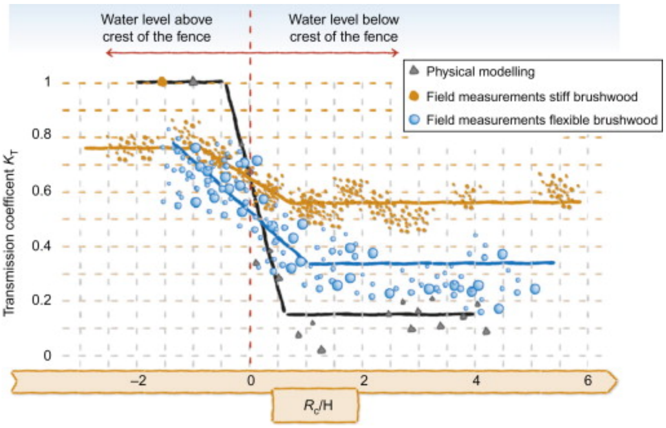
Figure 5.8: Materials and their applicable water depth

5.6.5. Wave Attenuation

The last requirement is the wave attenuation. The wave transmission over a breakwater is highly dependent on the design. Some breakwaters are designed primarily to attenuate, rather than completely dissipate, wave energy. This approach reduces wave intensity to protect shorelines and structures while allowing water movement and sometimes even sediment transport. Breakwaters like bamboo, wooden piles, floating breakwaters and submerged breakwaters are commonly used for wave attenuation. Bamboo and wooden piles are cost-effective and environmentally friendly, providing flexible barriers that absorb wave energy.



(a) Wave transmission through a pile screen
Source: From Grune and Kohlhase, 1974



(b) Wave transmission through a fence
Source: From Albers et al., 2013

Figure 5.9: Wave transmission through different structures

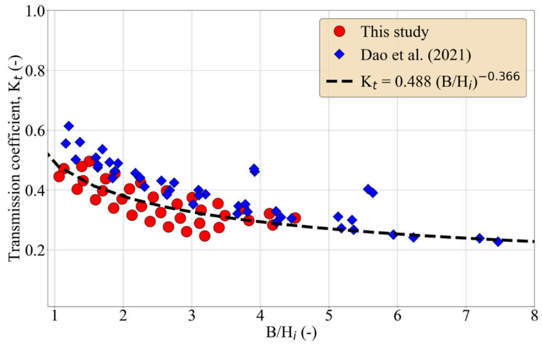
Figure 5.9a, illustrates the wave transmission through a pile screen, demonstrating how the wave transmission coefficient (K_t) decreases as the relative closure (W) increases. This indicates that piles are effective in attenuating wave energy, especially when spaced closely together. The measurements suggest that the efficiency of piles in wave attenuation depend on their arrangement and spacing. The closer the piles, the less wave energy passes through, making them a viable option for reducing wave intensity in various coastal protection scenarios. Two lines are indicated, with the striped line being an underestimation of the empirical expression indicated by the solid line (Grune and Kohlhase, 1974).

Figure 5.9b, shows wave transmission through a fence, highlighting the differences in effectiveness between stiff and flexible brushwood. The data reveals that wave transmission is lower when the water level is above the crest of the fence and higher when it is below. This suggests that the fence's height relative to the water level is crucial for its effectiveness. The flexible brushwood allows more wave energy to pass through compared to the stiff brushwood, indicating that material properties significantly influence wave attenuation. Fences, therefore, can be tailored to specific environmental conditions to optimize wave reduction (Albers et al., 2013). Similar, Figure 5.10 indicates the impact of parameters like fence thickness and wave length on the wave transmission through a fence.

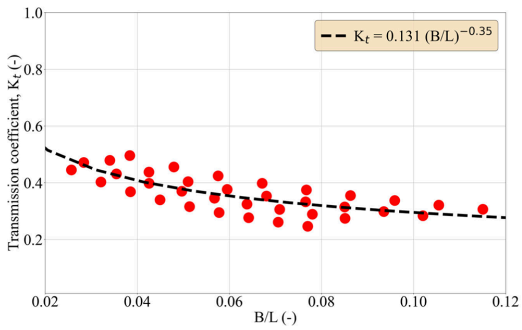
Floating breakwaters, made from materials like brushwood or flexible plastics, float on the water surface and are anchored to the seabed, moving with the waves to reduce their impact. These designs offer effective wave attenuation, enhancing coastal protection and resilience while maintaining natural coastal processes for limited wave heights. Nevertheless, when implementing floating breakwaters, special attention must be given to the anchorage due to its impact on wave damping. Proper anchorage is crucial for enhancing wave damping characteristics; however, it may also cause significant damage to brushwood mattresses. Therefore, it is recommended to conduct a detailed study before applying brushwood mattresses on a large scale in the field (Steeg and Wesenbeeck, 2011).

The left plot of Figure 5.11 shows that the transmission coefficient generally increases with wave height for both brushwood mattresses with widths of 4 meters and 12 meters, indicating that larger waves are less effectively attenuated by the mattresses. The right plot illustrates the relationship between the transmission coefficient and the relative length (w/L), showing that as the relative length increases, the transmission coefficient decreases, particularly for the brushwood mattress with a width of 4 meters. This suggests that longer relative lengths of the structure provide better wave attenuation.

Submerged breakwaters, or low-crested breakwaters (LCB), are designed to break incoming waves and generate vortices, thereby reducing the energy of the waves that pass over them. The effectiveness of



(a) Wave transmission through a fence depending on fence thickness and incoming wave height
Source: From Mai et al., 2023



(b) Wave transmission through a fence depending on fence thickness and wave length
Source: From Mai et al., 2023

Figure 5.10: Relative fence thickness with incoming wave height and wavelength

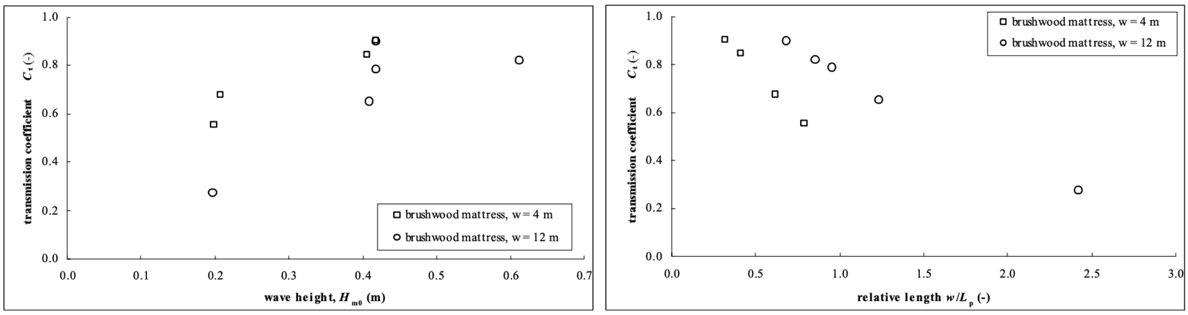
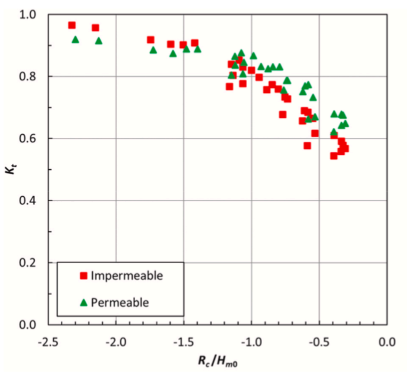
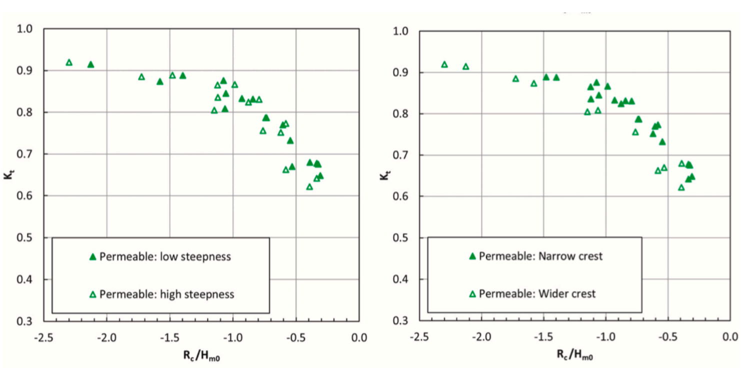


Figure 5.11: Transmission Coefficient C_t as function H_{m0} and as function of relative mattress length w/L_p
Source: From Steeg and Wesenbeeck, 2011



(a) Influence of relative crest height on wave transmission (van Gent et al., 2023)



(b) Influence of wave steepness and crest width on wave transmission (van Gent et al., 2023)

Figure 5.12: Wave transmission over a submerged rubble mound breakwater

submerged breakwaters largely depends on parameters such as relative crest freeboard (R_c/H_i) and the relative width of the breakwater (B/H_i). Studies indicate that for rubble mound breakwaters, as the crest freeboard increases from negative to positive values, the transmission coefficient (K_t) decreases (van Gent et al., 2023). For permeable rubble mound breakwaters, wave transmission varies with crest height and crest width, as can be seen in Figures 5.12a and 5.12b. Slightly submerged structures ($-1 < R_c/H_{m0} < 0$) exhibit a wave transmission coefficient of 0.8 to 0.6. Highly submerged structures ($-2.5 < R_c/H_{m0} < -1.5$) show larger wave transmission coefficients of close to 1. Wider crests consistently reduce wave transmission for both permeable and impermeable structures. Wave steepness also plays a role, with higher steepness leading to lower wave transmission, especially for impermeable structures.

5.6.6. General Performance of Materials

Selecting the appropriate material for breakwaters and other marine structures is the basis of the design. This selection depends on factors such as wave resistance, carbon emissions, durability, local availability, and depth versatility. Below, each material is separately being examined on its performance under extreme marine conditions, their sustainability, and their adaptability to different environmental contexts. This analysis aims to provide insights into the most effective materials for hydraulic applications.

1. MagnaDense Concrete

Magnadense Concrete is a high-density material ideal for extreme marine conditions, making it perfect for robust structures like breakwaters and sea defenses. Its high density reduces the amount of material needed, but it has a significant carbon footprint due to the transport distance. Future advancements in reducing transport emissions could lower these high emissions. Despite this, the material's exceptional durability ensures long-term stability and resilience.

2. Geopolymer Concrete

Geopolymer Concrete is known for its high stability under extreme conditions, similar to Magnadense Concrete. It has a projected high durability, similar to that of traditional concrete, but comes with moderate-to-high carbon emissions. Its availability is considered moderate due to the fluctuating supply of key precursors. Despite this, Geopolymer Concrete strikes a balance between high performance and sustainability, offering lower carbon emissions compared to traditional concrete. This material is suitable for various marine construction projects, providing a more eco-friendly alternative to conventional concrete while maintaining durability and strength.

3. Traditional Concrete

Concrete offers high stability and durability, making it a reliable choice for handling high wave heights and extreme marine conditions. However, it has a significant carbon footprint. Concrete is highly available within 200 km and adaptable across a broad range of water depths.

4. Rock

Rock provides moderate resistance to wave heights and offers stable alternatives where concrete may not be suitable. It exhibits high durability, potentially over 100 years, with relatively low carbon emissions. Rock is widely available locally within 200 km and is adaptable to water depths of up to 20 meters.

5. Brushwood Mattress

Brushwood Mattress can be applied in two forms and is a highly sustainable material with significantly negative carbon emissions, sequestering more CO_2 than it emits. Its wave resistance is limited, making it suitable for shallow waters typically less than 5 meters. It is ideal for erosion control and shoreline protection. While the durability of brushwood at water level is limited, it can extend up to 40 years when positioned below the water level.

6. Bamboo

Bamboo is another eco-friendly option with carbon-negative emissions. It shows limited wave resistance and short-term durability, making it suitable for specialized applications in shallow marine and freshwater environments. Bamboo is imported and relies on considerable lengths to be effective.

7. Geotextile Tubes

Geotextile Tubes, made from materials like jute or polypropylene (PP), offer low carbon emissions and are widely available due to extensive production and distribution networks. They are suitable for shallow waters but exhibit lower stability against large waves compared to rock and concrete. Covered geotubes can extend durability while maintaining reasonable emission levels, making them practical for projects requiring flexible, lower-emission materials. Polypropylene can last up to 100 years below the water level, but the potential release of microplastics into the environment makes it less favourable. Conversely, biodegradable materials like jute show very low durability.

8. Sediment Blocks

Sediment Blocks combine local dredged material with cement, providing a more sustainable option than traditional concrete. While their stability is assumed to be similar to rock rather than concrete, they still offer a moderate level of performance. Their carbon emissions are positive but moderate, and their projected durability could reach nearly 50 years. Sediment blocks are mostly available within a 200 km range, with potential for future scalability.

9. Hardwood and Softwood

Hardwood offers moderate wave resistance with carbon emissions influenced by sourcing and availability. Its durability ranges from 20 to 40 years, with potential future emission reductions due to improved carbon sequestration data. While hardwood is often sourced from greater distances, such as Africa and South America, softwood is generally available within a 1000 km range, indicating more regional availability. Both hardwood and softwood are suitable for specialized marine and freshwater applications, depending on their durability and environmental impact.

5.7. Evaluation and Selection of the best Alternative

5.7.1. Relative importance of the criteria

The evaluation design phase seeks to find a balance between the value created by a project and the sacrifices needed to achieve that value. It follows the verification phase, where potential design concepts are assessed against project requirements to ensure that only feasible alternatives proceed to evaluation. This phase aims to find a preferred alternative by systematically weighing the advantages and disadvantages of each concept, employing multi-criteria analysis (MCA) for greater objectivity.

With the feasible alternatives and evaluating criteria being defined, this step is to define the relative importance of the evaluating criteria. The relative importance is indicated by means of the comparison scale shown in Table 5.1. The values are based on the overall goal and purpose of the design. The relative importance of each criteria is shown in Figure 5.13. The comparison matrices for two cases are shown. This shows how the criteria for evaluating potential solutions can be shaped by the presence of carbon neutrality as either a foundational requirement or a criteria. The costs should be added as a separate criterion, ensuring sustainability and functionality first. The economical feasibility of the alternatives are presented by means of a value-cost graph.

- **Carbon Footprint:** As the primary goal is to design a carbon-neutral breakwater, minimizing the carbon footprint of materials and construction processes is the highest priority.
- **Local Availability:** Strongly connected to the carbon footprint, using locally sourced materials reduces transportation emissions and supports the local economy. Prioritizing materials that are readily available near the construction site is important for achieving carbon neutrality and reducing the overall carbon footprint of the project.
- **Energy Efficiency:** Closely linked to the carbon footprint, energy efficiency in the construction is crucial in reducing the overall environmental impact of the breakwater.
- **Ecosystem Impact:** Following the primary criteria of carbon footprint, energy efficiency, and local availability, ecosystem impact is the next most important factor. Ensuring that the breakwater design minimizes harm to the surrounding marine and coastal environments is of great importance. Protecting ecosystems helps maintain biodiversity, water quality, and natural processes, which are integral to long-term environmental sustainability.
- **Robustness:** While robustness is important for the structural integrity and longevity of the breakwater, it should be balanced with environmental considerations. Ensuring the breakwater can withstand harsh marine conditions is necessary, but this should not come at the expense of excessive carbon emissions or ecological damage.
- **EoL planning:** Planning for the end-of-life phase of the breakwater is important for ensuring that materials can be reused, recycled, or disposed of in an environmentally responsible manner. However, since breakwaters are typically constructed to be permanent, this criterion holds less significance.

Table 5.1: Relative importance for alternative pairs.

Intensity of importance	Definition
1	Equal importance
2	Medium importance of one over the other
3	Absolute importance

- A value of "1" indicates equal importance between two alternatives.
- Values greater than "1" suggest a preference for the alternative on the row over the one on the column.
- Values less than "1" (expressed as fractions) indicate a preference for the alternative on the column over the one on the row.

(a) Comparison Matrix

Column		a	b	c	d	e	Total
Ecosystem Impact	**a**	1	1	1/2	1/2	2	5
Robustness	**b**	1	1	1/2	1/2	2	5
Local Availability	**c**	2	2	1	1	2	8
Energy Efficiency	**d**	2	2	1	1	2	8
EoL planning	**e**	1/2	1/2	1/2	1/2	1	3

(b) Determination of the weighting factors

		Weighting Factor
a	5	0.172
b	5	0.172
c	8	0.276
d	8	0.276
e	3	0.103
	Σ29	Σ1

(c) Comparison Matrix (Carbon Footprint as criterion)

Column		a	b	c	d	e	f	Total
Ecosystem Impact	**a**	1	1	1/2	1/2	2	1/2	5.5
Robustness	**b**	1	1	1/2	1/2	2	1/2	5.5
Local Availability	**c**	2	2	1	1	2	1/2	8.5
Energy Efficiency	**d**	2	2	1	1	2	1/2	8.5
EoL planning	**e**	1/2	1/2	1/2	1/2	1	1/3	3.33
Carbon Footprint	**f**	2	2	2	2	3	1	12

(d) Determination of the weighting factors

		Weighting Factor
a	5.5	0.127
b	5.5	0.127
c	8.5	0.196
d	8.5	0.196
e	3.33	0.077
f	12	0.277
	Σ43.33	Σ1

Figure 5.13

5.7.2. Scoring the Alternatives per Criterion

The pairwise comparison method is the following component of the MCA, providing decision-makers the ability to evaluate and prioritize alternatives by comparing them two at a time. In the process of making pairwise comparisons, it is crucial to maintain consistency in judgements. Pairs of alternatives are compared relative to their importance towards a criterion or the overall goal. This step-by-step comparison across all levels emphasizes the need for consistent reasoning to ensure the reliability of the analysis. For simplicity, the previous identified scale will be applied in this step as well.

5.7.3. Determine the overall ranking

Once the priority scores for each alternative are determined, the next step is to integrate these scores with the relative importance of the criteria, essentially multiplying the scores by the criteria weights. This calculation produces an overall score for each alternative, considering every criterion. By summing these scores for each alternative, a final, aggregated score is obtained that represents the alternative's overall performance across all evaluated criteria. A comprehensive ranking is achieved that reflects both the individual evaluations of alternatives against each criterion and the priorities of the decision criteria. Consequently, the alternative that scores the highest is the most suitable option according to the MCA analysis. The last step is to check whether the alternative is economically feasible.

5.8. Final Design Selection

The final phase of the process involves making a decision on the actual design. This phase refines the selected alternative into the final design, focusing on practical implementation and ensuring that it meets the carbon neutrality requirements established at the beginning. This stage builds on the foundation laid by previous steps: system analysis, precise definition of requirements, and the establishment of evaluation criteria. These steps were followed by the development and verification of multiple design concepts, which were then evaluated based on predefined criteria. By following this structured progression, the chosen solution is shaped into a comprehensive and practical design that incorporates the goals and principles established during the design process. If it is not possible to establish a carbon-neutral design under the given circumstances and requirements, alternative scenarios can be considered by going back to the requirements. In these scenarios, the requirements may be slightly altered to create a design that can achieve carbon neutrality.

5.9. Concluding Remarks

The approach to building a carbon-neutral breakwater includes some adaptations and additions with respect to the traditional method. The primary goal of a carbon-neutral breakwater is to minimize the carbon footprint throughout its entire lifecycle, considering CO_2 emissions from material production, transportation, construction, and maintenance.

Traditional breakwaters typically use conventional materials like concrete and rock, selected for their proven durability and cost-effectiveness, but these materials often come with higher environmental impacts due to carbon-intensive production processes. In contrast, the carbon-neutral approach incorporates Life Cycle Assessment (LCA) criteria to evaluate the environmental impact of materials and construction methods over the entire lifecycle of the breakwater. This includes considerations like energy efficiency, end-of-life planning, and ecosystem impact. Traditional breakwaters may not systematically include LCA criteria in their design and construction processes, often treating environmental considerations as secondary to immediate practical and economic concerns.

A thorough evaluation process is employed in the carbon-neutral approach, developing and verifying multiple design alternatives against both traditional and environmental criteria. This ensures that the selected design is both effective and sustainable. In contrast, traditional breakwater construction typically focuses on verifying designs primarily against structural and functional requirements, with less rigorous evaluation of environmental impacts.

Innovation and adaptability are key components of the carbon-neutral approach, encouraging design strategies that allow for modularity and the incorporation of new sustainable technologies as they develop. Traditional breakwaters often rely on established, conventional designs that prioritize immediate functionality and cost, offering less flexibility for integrating innovative materials or methods.

The use of locally available materials is prioritized in the carbon-neutral approach to reduce transportation emissions and minimize ecological disruption. Traditional breakwaters may use materials sourced from farther away if they are more cost-effective or readily available, often without focusing on the environmental impact of transportation and material extraction.

In summary, the approach to building a carbon-neutral breakwater is characterized by a comprehensive focus on sustainability, incorporating environmental impact assessments, the use of eco-friendly materials, and innovative design practices to achieve long-term ecological and economic benefits. This adaptation of the traditional approach, will highlight the need for further research in several areas. Integrating ongoing research into this approach will enhance its effectiveness and ensure that future breakwater projects align with both ecological sustainability and practical viability.

6

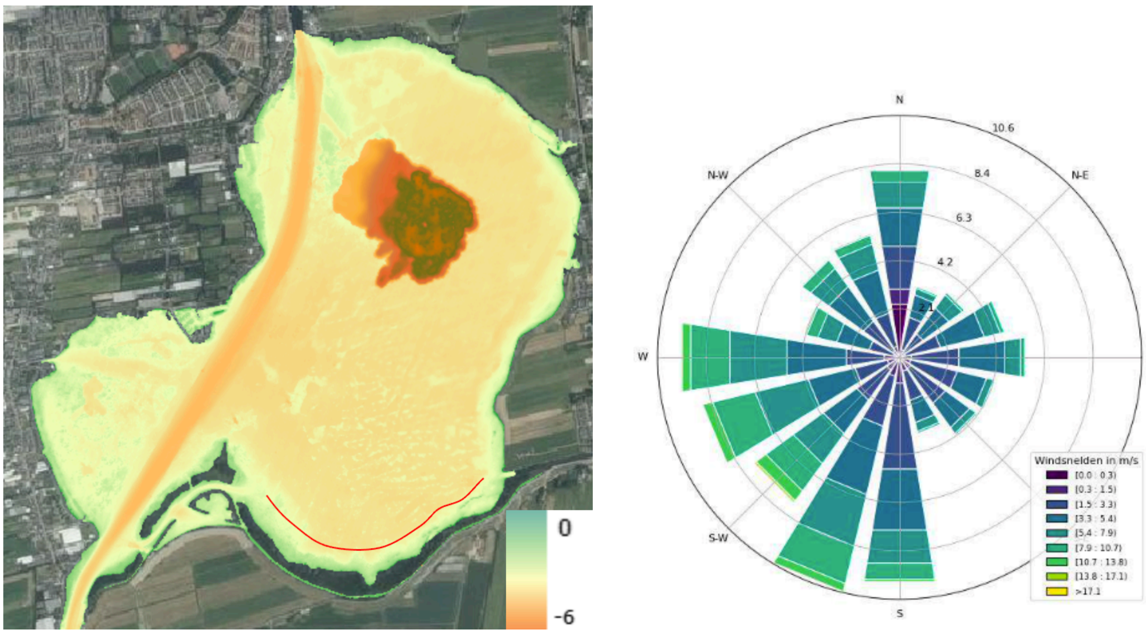
Verification of the Design Approach: Case Study Braassemermeer

6.1. Introduction

Based on the design approach described in the previous chapter, breakwater designs, based on different materials, will be evaluated by means of a case study. The boundary conditions will be determined by the location of the case study. The location for this analysis is the Braassemermeer. For this project, the aim is to build a breakwater on the south side of Braassemermeer, a freshwater lake. The primary goal of the breakwater is to reduce wave energy and consequently, provide a nature-friendly environment in the sheltered zone. The second objective is to construct a breakwater that is carbon neutral. In the next steps, the flow chart (Figure 5.1) will be followed. The definitions of the evaluation criteria are already provided in Section 5.4, and will not be repeated here, but referred to when needed.

6.2. System Analysis

6.2.1. Wind Data



(a) Braassemermeer depth map

(b) Wind Rose Diagram

Figure 6.1: Braassemermeer

The depth map in Figure 6.1a, shows the location of the breakwater. The breakwater will be constructed in water depths between 2 to 3 meters. Furthermore, the fairway is indicated by the strip of deeper water and a sand extraction area is shown in the northern part of the lake. The wind rose diagram in Figure 6.1b, illustrates the prevailing wind directions and speeds in the area from 2014 to 2023 (see Figure C.3), specifically highlighting the significance of winds coming from the west-northwest (WNW) to northeast (NE). In this region, wind is the primary driver of wave formation on the Braassemermeer, with these directional winds having the largest fetch. The fetch, essentially the distance over water that the wind blows without interruption, greatly influences wave size and energy and causes wind setup. The critical storm conditions are determined by means of a simple comparison between storms coming from different directions. The historical wind data is extrapolated to achieve the conditions with a return period of 1/100 years. One dominant direction is from the west-northwest and the other is from the north. The west-northwest has a fetch length of 2200 meters, while the north has a longer fetch of 2500 meters, which can be seen in Figure C.2b and C.2a. The wind setup, a crucial consideration due to its potential significant effect on water levels, is calculated for dominant wind directions in Appendix C. The resulting wind setup is 0.025 meters, which is probably not substantial enough to impact the design significantly.

6.2.2. Hydraulic Conditions

Using the wind rose diagram and the analysis method by Young and Verhagen, wave conditions are derived under varying water depths ranging from 2 meters to 5 meters deep, as shown in Tables 6.1 and 6.2.

Table 6.1: Wave conditions for direction: N

Depth (m)	**2**	**3**	**4**	**5**
$\mathbf{H_s}$ **(m)**	0.38	0.39	0.4	0.4
$\mathbf{T_p}$ **(s)**	2.5	2.55	2.57	2.58

Table 6.2: Wave conditions for direction: WNW

Depth (m)	**2**	**3**	**4**	**5**
$\mathbf{H_s}$ **(m)**	0.39	0.4	0.41	0.42
$\mathbf{T_p}$ **(s)**	2.53	2.58	2.6	2.61

The governing values for the wave height and the wave period that will be used for the design of the breakwater will be $H_s = 0.42$ m and $T_p = 2.61$ s.

6.2.3. Subsoil Data

There is no specific soil data available of the exact location on which the breakwater will be constructed. However, there is some data available of other parts of the Braassemermeer. For this case, the subsoil is assumed to be similar to the available soil data closest to the breakwater's exact location, which can be seen in Figure C.1. The subsoil of the Braassemermeer consists of a very weak peat layer for the top 5 meters, with similar weak underlying layers exhibiting low cone resistance down to approximately NAP-12 meters. This weak subsoil significantly impacts the design of structures, requiring careful consideration to ensure stability. Foundations must be designed to avoid excessive settlement, often necessitating interventions. Soil improvement techniques like consolidation, stabilization, or the use of fascine mattresses for stabilization can enhance load-bearing capacity. Additionally, choosing lightweight structures such as pile screens or other light constructions can help prevent or minimize settlements. Nevertheless, the subsoil needs to provide enough stability for the piles. Still, options like this mitigate risks and ensure the long-term stability and performance of breakwaters in this area.

6.3. Defining Requirements

For this project, which is aimed at creating a sheltered zone where reeds can develop and aquatic plants can survive, the design and construction of the breakwater must meet specific requirements set to support this ecological objective. Structural requirements, environmental requirements and functional requirements must ensure the design of the breakwater fits in the environment. These requirements are based on boundary conditions, starting points and actual requirements.

Structural Requirements:

- Stability: The breakwater must be engineered to withstand specific wave heights, which in this region could reach up to 0.42 meters during storm conditions. This ensures stability against the physical forces of waves, currents.
- Strength: The construction materials must be selected for long-term endurance, capable of resisting the corrosive marine environment for a minimum of 50 years without significant maintenance or degradation.

Environmental Requirements:

- Environmental Impact: The design should not have any negative impact on the environment. With this it is meant that geotextiles made from PP, which may release microplastics into the environment, can not be utilized.
- Carbon Footprint: The design should incorporate materials and construction methods that minimize carbon emissions and eventually lead to a carbon neutral breakwater, meaning 0 kg of CO_2 emissions over the complete life-cycle stages of the breakwater. Emphasis should be on sustainable practices, including the use of renewable resources or recycled materials where possible.
- Resource Availability: Enough material should be available to build the breakwater over the complete length of 1500 meters.

Functional Requirements:

- Wave Attenuation: The breakwater should reduce incoming wave energy, facilitating calm conditions that are ideal for the growth of reeds and aquatic plants. For the growth of the plants, temporary protection is recommended. In the first years, wave heights up to 0.2 meters are acceptable as reed can withstand these conditions. Eventually, reed can handle daily wave heights of 0.25 meters and occasional waves up to 0.40 meters (no more than 5000 waves per year and not consecutively) (CUR, 1999).
- Ecological Impact: The design must prioritize ecological sustainability, avoiding disruption to local marine life and habitats. Measures should be taken to enhance biodiversity, such as incorporating features that serve as artificial reefs or promote marine colonization.

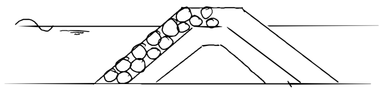
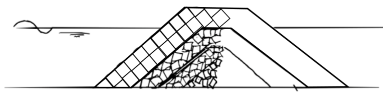
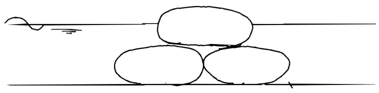
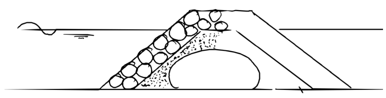
Each of these requirements addresses the critical aspects of the breakwaters function, structural integrity, and environmental impact, ensuring that the project not only meets its protective role but also enhances the habitat for aquatic plants and local wildlife.

6.4. Development of Breakwater Design Concepts

In this section design concepts are introduced based on conventional and alternative materials. In the following sections, these designs will be verified according to the requirements.

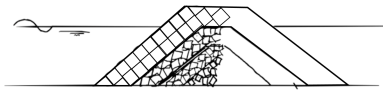
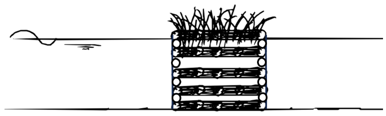
Conventional Breakwater Concepts

Table 6.3: Conventional Breakwater Design Concepts with Images

Breakwater Design Concept	Image
Rubble Mound Rock: A traditional breakwater type using naturally sourced rocks piled to form a barrier against waves.	
Rubble Mound Concrete: A conventional rubble mound structure made from concrete units that offers stability and durability.	
Geopolymer Concrete: A breakwater made from dense geopolymer concrete with a higher strength-to-weight ratio.	
MagnaDense Concrete: Uses a heavy concrete made with MagnaDense, a natural iron oxide, for increased density and stability.	
Rubble Mound Rock & Concrete Units: A hybrid design combining rock with concrete elements to enhance structural integrity.	
Rubble Mound Rock & High-Density Geopolymer Concrete: A mixture of rock and high-density geopolymer concrete to reduce the structures carbon footprint.	
Geotextile Tubes: Cylindrical bags made from geotextile fabric, filled with sand or dredged materials, used to absorb wave energy.	
Jute Tubes: Cylindrical bags made from jute, filled with sand or dredged materials, used to absorb wave energy.	
Geotextile Tubes with Rock Layer: Geotextile tubes topped with a layer of rock to enhance weight and stability.	
Geotextile Tubes with Concrete Armour Units: Geotextile tubes covered with concrete armour for added protection.	

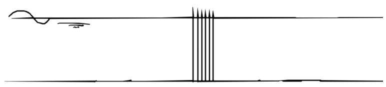
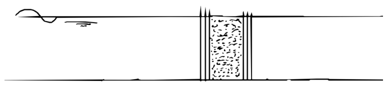
Breakwater Design Concepts with Alternative Materials

Table 6.4: Breakwater Concept with Alternative Materials with Images

Breakwater Design Concept	Image
Sediment blocks: Blocks made from compacted sediment, offering an alternative that may integrate with the local ecosystem.	
Brushwood Grids Stacked: Grids made from brushwood, filled with local dredged material to make it sink. Leaving the brushwood grids below water level.	
Brushwood Grids Stacked with rock protection: Grids made from brushwood, filled with local dredged material to make it sink. Leaving the brushwood grids below water level.	

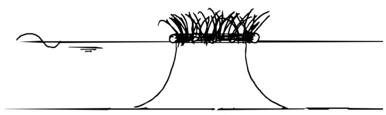
Permeable Breakwater Design Concepts

Table 6.5: Permeable Breakwater Design Concepts with Images

Breakwater Design Concept	Image
Bamboo pile screen: A highly sustainable and lightweight option using bamboo to reduce wave energy while allowing water to flow through.	
Timber pile screen: Breakwaters constructed from wood, offering some permeability and blending with natural surroundings.	
Bamboo/Brushwood Fence: 2 rows of bamboo piles, filled with brushwood to damp the waves.	
Timber/Brushwood Fence: 2 rows of timber piles, filled with brushwood to damp the waves.	

Floating Breakwater Concepts

Table 6.6: Floating Breakwater Concepts with Images

Breakwater Concept	Image
Floating Brushwood Mattress: Woven willow branches on which reeds (or other types) are planted, creating a floating marsh.	

6.5. Verification of design concepts

The design concepts are verified based on the starting points, boundary conditions and the requirements, which are summarized in Table 6.7. These concepts must meet the requirements to ensure their suitability for long-term application. The requirements include the ability to withstand significant wave heights of up to 0.42 meters without causing any damage to the structure, demonstrating sufficient wave attenuation to reduce waves to less than 0.2 meters behind the breakwater. Additionally, these designs must show durability, lasting at least 50 years to ensure prolonged protection. Environmental considerations are crucial, requiring zero or negative carbon emissions to mitigate climate impact and ensuring no release of microplastics into the environment. Lastly, the designs must be capable of functioning effectively in water depths of 3 meters. In this section, figures will be used to identify the most viable and sustainable design concepts. With red designs being not suitable and thus eliminated. Green designs on the other hand, are suitable with respect to that particular requirement.

Table 6.7: Defining the Basis of the Breakwater Designs

Starting Point	**Description**
Durability	50 years
Breakwater Length	1500 meters
Boundary Condition	**Description**
Wave Height	0.42 meters
Water Depth	3 meters
Subsoil	Soft peat layer
Water type	Fresh
Requirement	**Description**
Wave Attenuation	$H_t <$ 0.2 meters behind breakwater
Carbon Emissions	≤ 0 kgCO_2/m^3
Microplastics	No use of geotextiles made from plastics

Note: The data presented in the figures are based on currently available information and should not directly be taken as absolute truth. They provide an indication of the potential outcomes, and as new data becomes available, the graphs and consequently, the conclusions, may change accordingly.

6.5.1. Verification Based on Carbon Footprint
Wave Height

Several materials can be eliminated based on their high carbon emissions and ability to handle wave heights. Rock, Concrete, Geopolymer Concrete, Geotubes (PP), and MagnaDense Concrete are all unsuitable, marked in red, due to their high carbon emissions despite their varying capacities to handle high wave heights. Hardwoods from South America, Africa, and Europe, along with Sediment Blocks, also have high carbon emissions, making them environmentally unsuitable even though they can manage moderate wave heights.

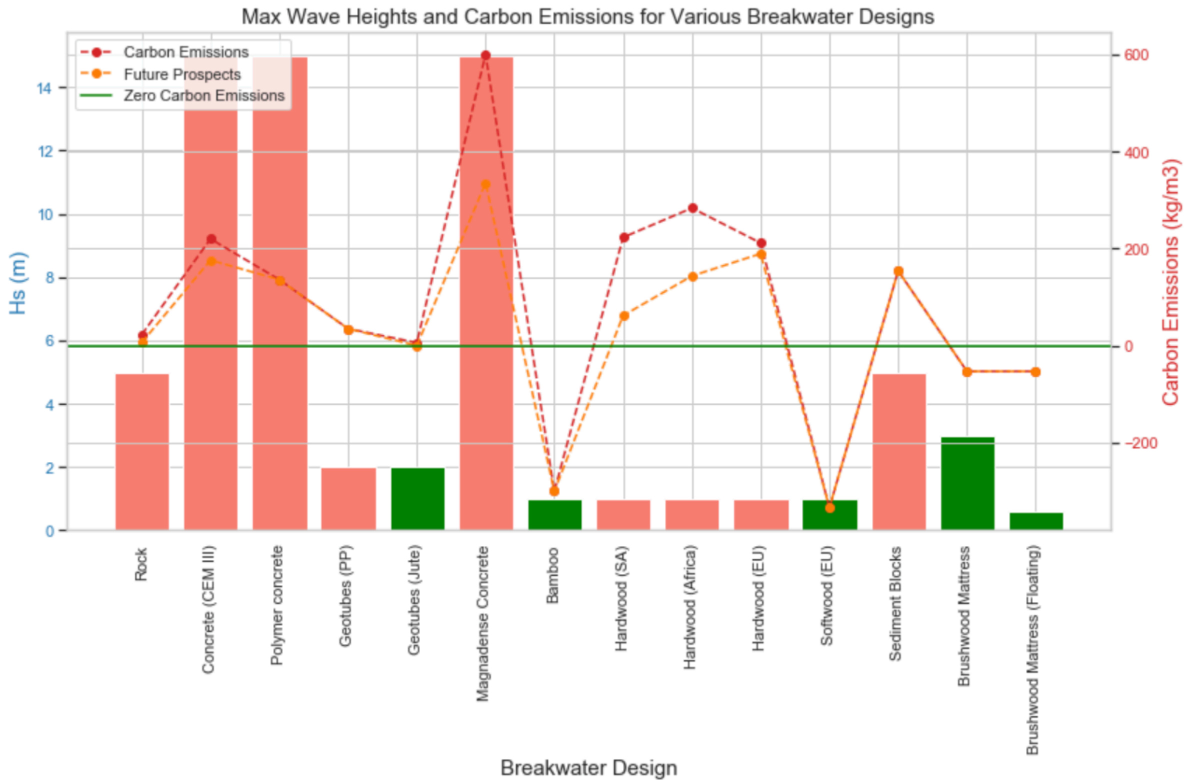


Figure 6.2: Elimination of designs based on zero carbon emissions and wave height of 0.42 m

Conversely, materials like Geotubes made from Jute, Bamboo, Softwood (EU), Brushwood Mattress, and Brushwood Mattress (Floating) are highlighted in green, indicating their suitability. Bamboo and Brushwood Mattresses, both standard and floating, have negative carbon emissions and can manage moderate wave heights, making them environmentally favourable options. Softwood (EU) also shows negative carbon emissions but handles lower wave heights, suggesting it is suitable for specific, less demanding coastal environments. Table 6.8 summarizes the suitable breakwater concepts.

Table 6.8: Summary of Suitable Breakwater Design Concepts Based on Wave Height and Carbon Emissions

Breakwater Design Concepts
Brushwood grids stacked
Brushwood grids stacked with rock protection
Floating Brushwood Mattress
Bamboo Pile screen
Timber (softwood) Pile screen
Bamboo/Brushwood Fence
Timber/Brushwood Fence
Geotubes (Jute)

Strength

Based on the analysis indicated in Figure 6.3, no single material meets both the 50-year durability threshold and the zero carbon emissions goal simultaneously. The green area indicates where suitable materials should be located, but currently, no material meets both criteria. High durability materials such as MD Concrete, Concrete, Geopolymer Concrete, and Rock have very high carbon emissions, making them environmentally unsuitable. Conversely, materials like Bamboo, Softwood (EU), Brushwood, and Geotubes (PP and Jute) have low or negative carbon emissions but fall short of the 50-year durability mark, ranging from 10 to 40 years. Therefore, each material presents trade-offs between durability and environmental impact, indicating the problem that no material is currently suitable under both criteria.

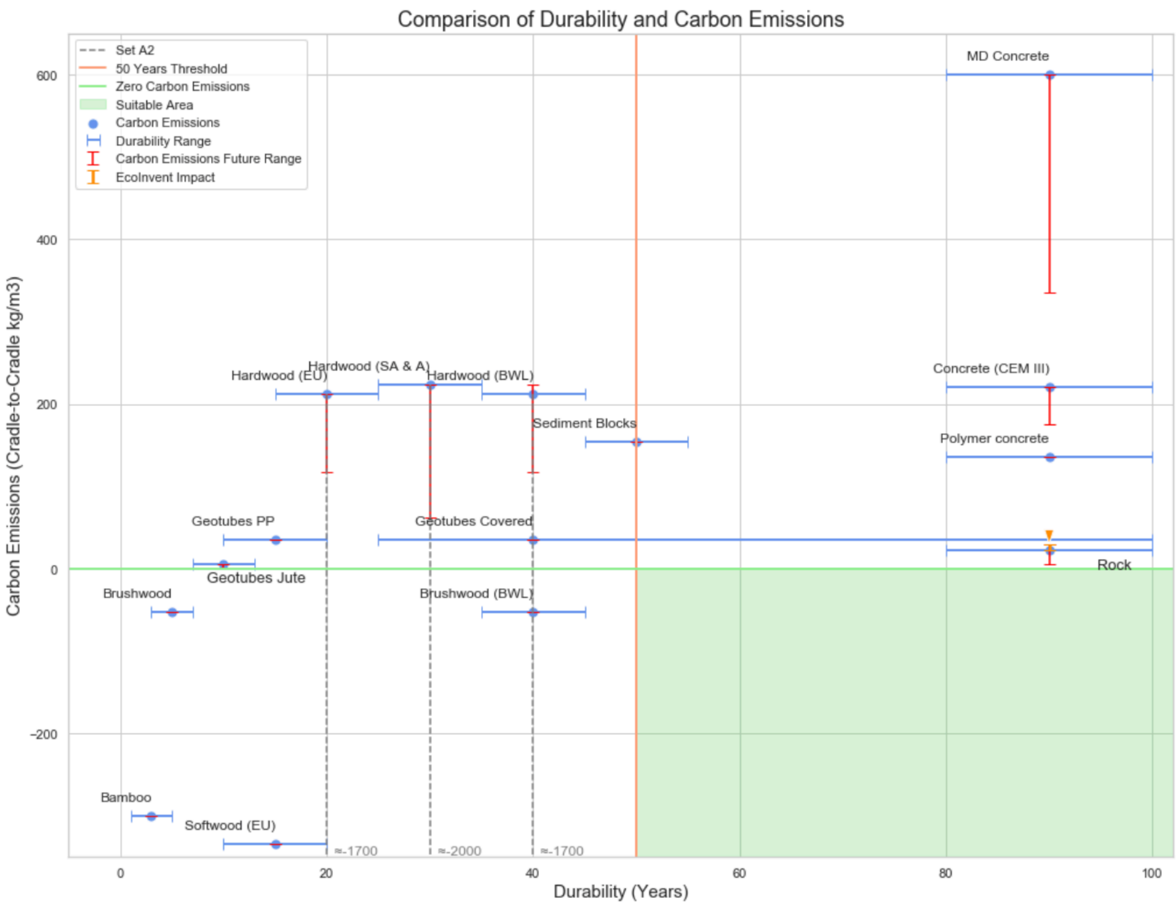


Figure 6.3: Elimination of designs based on carbon emissions and durability of the materials

Table 6.9: Summary of Suitable Breakwater Design Concepts Based on Durability and Carbon Emissions

Breakwater Design Concept

Availability

Figure 6.4 shows the analysis of the availability of materials categorized by local range. Assuming the future prospects of sediment blocks, it can be concluded that all materials are capable of providing sufficient quantities for breakwaters longer than 1500 meters. The production of sediment blocks is not yet well-developed, resulting in limited availability. However in the near future this is assumed to be no hurdle anymore, due to scalability. The rest of the materials are assumed to offer sufficient availability for this breakwater project.

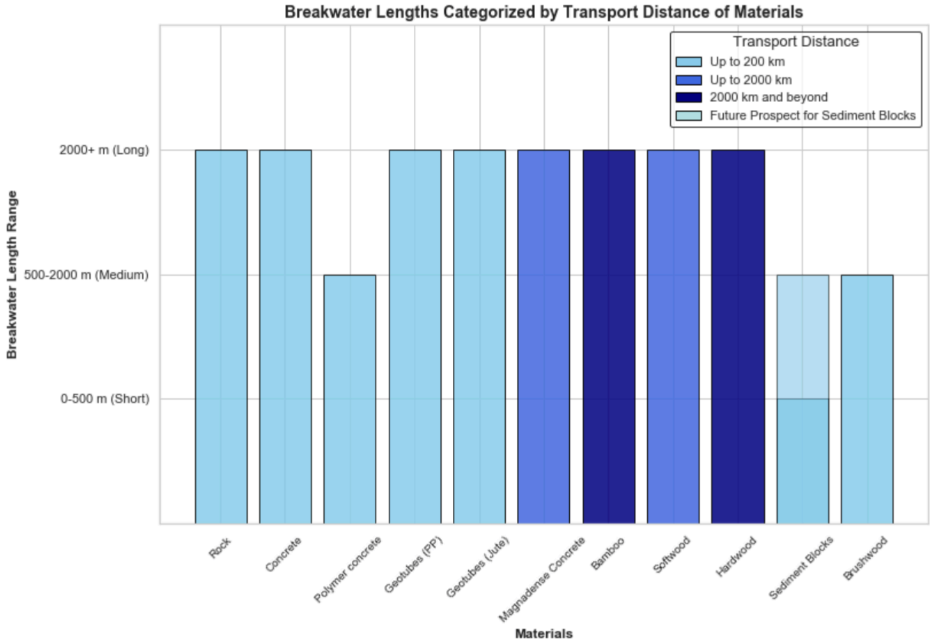


Figure 6.4: Elimination of designs based on the availability of the materials

Water Depth

Figure 6.5 illustrates the range of water depths suitable for various breakwater designs, specifically focusing on their applicability for water depths of 4 meters. Designs such as Brushwood Mattress (Floating), Brushwood Mattress, Sediment Blocks, MagnaDense Concrete, Geotubes, Geopolymer Concrete, Concrete, and Rock RM, marked in green, are suitable for water depths of 4 meters and beyond, making them versatile for various marine environments. In contrast, Timber Fences and Bamboo Fence, marked in red, are not suitable for water depths of 4 meters, as their maximum applicable depth does not meet this threshold. Therefore, while most breakwater designs are appropriate for deeper water applications, Timber Fences and Bamboo Fence are better suited for shallower waters. The selection of breakwater design should consider this depth suitability criterion to ensure optimal performance and stability.

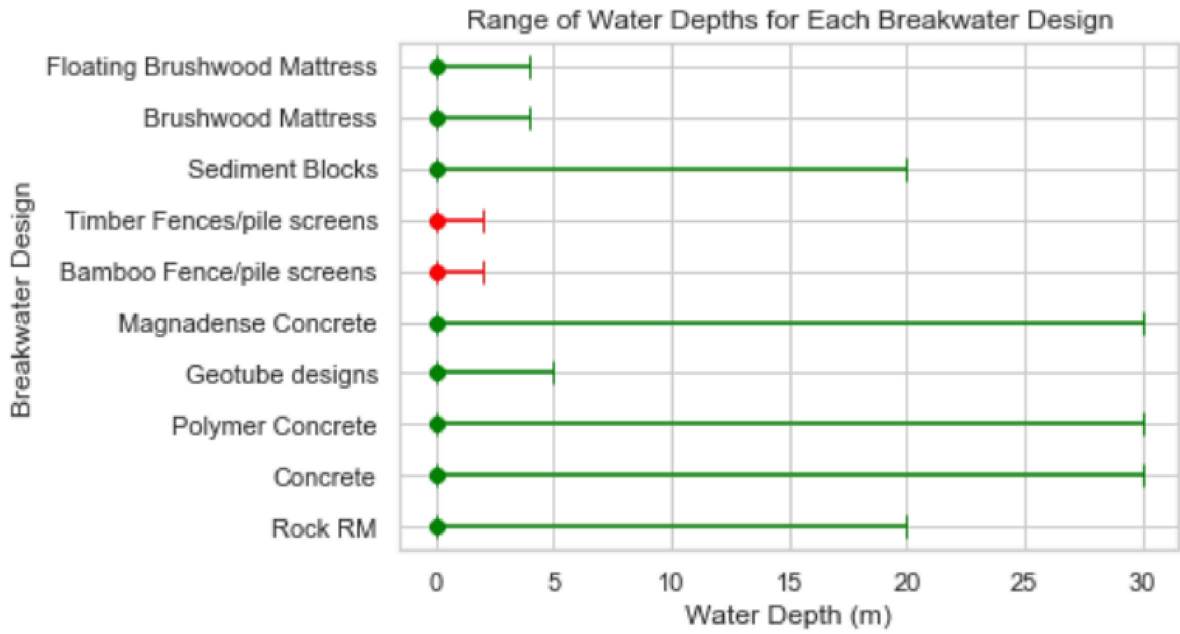


Figure 6.5: Elimination of designs based on the applicability to certain water depths

Table 6.10: Summary of Suitable Breakwater Design Concepts Based on applicability in water depth

Breakwater Design Concept
Rubble Mound Rock
Concrete
Sediment Blocks
Geopolymer Concrete
MagnaDense Concrete
Rock & Concrete
Brushwood grids stacked
Brushwood grids stacked with rock protection
Floating Brushwood grids
Geotubes PP
Geotubes Jute
Geotube (PP) with Armour Layer

Wave Attenuation

The last requirement is the capability of attenuating waves. The graphs provided in the Methodology chapter on wave attenuation (Section 5.6.5), offer insight into the wave attenuation performance of the various breakwater designs. When the significant wave height is 0.42 meters and the required wave height behind the breakwater is 0.2 meters, the design requirements of the breakwater configurations can be derived. This analysis focuses on breakwaters that do not completely attenuate waves, specifically timber fences, bamboo fences, timber pile screen, bamboo pile screen, floating brushwood mattress and submerged breakwaters. The dissipation of wave energy by a construction highly depends on the configuration of the designs.

Figure 5.9a, presents the transmission coefficient as a function of relative closure for pile screens. The analysis indicates that for relative closures W ≥ 0.2, timber and bamboo pile screens achieve transmission coefficient values below the 0.47 threshold, thus effectively attenuating the wave height to the required level. When a fence made from bamboo or timber is applied, one has to look at Figures 5.9b and 5.10. According to these figures, the crest should slightly extend out of the water to achieve a transmission coefficient of 0.47. A different configuration has to do with the fence thickness. The fence thickness should be approximately 3 meters to manage a wave height of 0.42 meters.
Furthermore, the wave attenuation of floating brushwood mattresses is given in Figure 5.11. The right plot, shows the relation between the transmission coefficient and the relative length of the mattress (the ratio between the length of the mattress and the peak wave length). A brushwood mattress with a length of 12m is only suitable with a relative length of about 2.5, consequently meaning a peak wave length of 4.8m or lower. It should be noted, that the focus here lies on the wave attenuation, but forces of the waves exerted on the foundation of the mattresses, can still lead to an unfeasible structure.

The last design is the low-crested rubble mound breakwater. Figure 5.12, indicates the relative crest height it requires to sufficiently reduce the wave transmission. Although the permeable rubble mound breakwater does not reach the red line. It can be assumed, by extrapolating the trend of the data points, that impermeable structures will achieve a K_t below 0.47 at approximately $R_c/H_{m0} = 0$, suggesting a well performance in wave attenuation. This analysis highlights that permeable submerged rubble mound breakwaters are efficient in attenuating waves and reach effective performance at higher crest free boards relative to wave height.

In conclusion, the breakwaters under consideration, demonstrate the ability to attenuate waves from a significant height of 0.42 meters to a required height of 0.2 meters in certain configurations. With all designs having transmission coefficients below the value of 0.47. This makes them suitable for scenarios where complete wave attenuation is not necessary but effective wave reduction is required. No design is eliminated in this case, but there should be carefully looked at the suitable configuration of the construction.

Conclusion of Verification

To conclude, no design meets all the specified requirements when carbon emissions are treated as a hard requirement. The verification process, which evaluated the designs against criteria such as wave height, wave attenuation, durability, availability, and water depth, revealed significant trade-offs. Materials like Rock, Concrete, Geopolymer Concrete, and MagnaDense Concrete, while highly durable, were found to have high carbon emissions, rendering them environmentally unsuitable. Conversely, materials with lower or negative carbon emissions, such as Bamboo, Softwood (EU), Brushwood, Geotubes (PP and Jute) and brushwood, did not meet the 50-year durability threshold, with lifespans ranging from 10 to 40 years. This analysis underscores that no single material satisfies both the environmental impact and durability criteria simultaneously. Given that no design meets all requirements with carbon emissions as a hard requirement, a new validation approach will be undertaken where carbon emissions are considered as an evaluating criterion rather than a strict requirement. This re-evaluation aims to identify designs that offer a balanced compromise between environmental impact and functional performance.

6.5.2. Concession: Verification with Carbon Emission as an Evaluation Criterion

Wave Height

Without the constraint of carbon emissions and thus only considering a wave height of 0.42 meters, the best materials for breakwater design would be those that effectively handle such mild conditions while potentially offering lower environmental impact. Materials like Geotubes (PP and Jute), Brushwood Mattress (Floating), and Bamboo are particularly suitable in this context. Geotubes, both PP and Jute, demonstrate adequate performance for low wave heights, providing effective protection without the need for the high durability required in more extreme conditions. Similarly, Brushwood Mattress (Floating) and Bamboo also perform well under these gentle wave conditions. These materials not only meet the functional requirements but also tend to have lower carbon emissions, making them more environmentally friendly choices when carbon emissions are not a stringent constraint. Thus, for a wave height of 0.42 meters, Geotubes, Brushwood Mattress (Floating), and Bamboo stand out as the best options in terms of hydrodynamic behaviour. Table 6.11 summarizes the suitable breakwater concepts.

Table 6.11: Summary of Suitable Breakwater Design Concepts Based on Wave Height

Breakwater Design Concept
Rubble Mound Rock
Concrete
Geopolymer Concrete
MagnaDense Concrete
Sediment Blocks
Brushwood Grids Stacked
Brushwood grids stacked with rock protection
Floating Brushwood Grids
Bamboo Pilescreen
Timber Pilescreen
Bamboo Fence
Timber Fence
Geotubes PP
Geotubes Jute
Geotube (PP) with Armour Layer

Durability

In the case of carbon emissions not being a hard requirement, the selection of materials can focus primarily on meeting the 50-year durability threshold. In this scenario, materials such as MD Concrete, Concrete, Geopolymer Concrete, Rock, and Sediment Blocks become suitable options. These materials offer high durability, with lifespans ranging from 50 to 100 years, ensuring long-term structural integrity and effectiveness in breakwater design. While they have higher carbon emissions, their durability makes them viable candidates when environmental impact is a secondary consideration. Thus, prioritizing durability allows for the selection of robust materials that can provide lasting protection.

Table 6.12: Summary of Suitable Breakwater Design Concept Based on Durability

Breakwater Design Concept
MagnaDense Concrete
Concrete
Geopolymer Concrete
Rock
Rock & Concrete
Sediment Blocks
Geotube (PP) with Armour Layer

Availability

With carbon emissions as an evaluating criterion, the availability of materials becomes crucial in selecting suitable breakwater designs. Most materials, including Rubble Mound Rock, Concrete, Geopolymer Concrete, MagnaDense Concrete, Brushwood grids, Floating Brushwood mattress, Bamboo Pile screen, Timber Pile screen, Bamboo Fence, Timber Fence, Geotubes (PP and Jute), and Bamboo, offer sufficient availability for constructing breakwaters longer than 1500 meters. The primary exception is Sediment Blocks, whose production is not yet well-developed, leading to limited availability. However, due to its scalability, it is assumed that production will become sufficient in the near future to meet the demands for this length of a breakwater.

Table 6.13: Summary of Suitable Breakwater Design Concepts Based on Material availability

Breakwater Design Concept
Rubble Mound Rock
Concrete
Geopolymer Concrete
MagnaDense Concrete
Rock & Concrete
Brushwood grids Stacked
Brushwood grids stacked with rock protection
Floating Brushwood Mattress
Bamboo Pilescreen
Timber Pilescreen
Bamboo/Brushwood Fence
Timber/Brushwood Fence
Geotubes PP
Geotubes Jute
Geotube (PP) with Armour Layer
Sediment Blocks

Water Depth

When carbon emissions are treated as an evaluating criterion, several breakwater designs remain suitable for varying water depths. Designs such as Brushwood Mattress (Floating), Brushwood Mattress, Sediment Blocks, MagnaDense Concrete, Geotubes (PP and Jute), Geopolymer Concrete, Concrete, and Rock RM are effective for water depths of 4 meters and beyond. These designs offer versatility for a wide range of marine environments, ensuring stability and effective performance in deeper waters. Conversely, Timber Fences and Bamboo Fences are better suited for shallower waters, as their maximum applicable depth does not meet the 4-meter threshold.

Table 6.14: Summary of Suitable Breakwater Design Concepts Based on applicability in water depth

Breakwater Design Concept
Rubble Mound Rock
Concrete
Geopolymer Concrete
MagnaDense Concrete
Sediment Blocks
Brushwood grids
Brushwood grids stacked with rock protection
Floating Brushwood Mattress
Geotubes PP
Geotubes Jute
Geotube (PP) with Armour Layer

Wave Attenuation

When considering wave attenuation with carbon emissions as an evaluating criterion, certain breakwater designs demonstrate the ability to reduce wave heights effectively. Designs such as Timber Fences, Bamboo Fences, Timber Pile screen, Bamboo Pile screen, and Floating Brushwood Mattress are particularly notable. These designs achieve transmission coefficients below 0.47, effectively attenuating waves from a significant height of 0.42 meters to the required height of 0.2 meters. These breakwaters have a suitable hydraulic performance for scenarios where complete wave attenuation is not necessary but effective wave reduction is required, ensuring adequate protection while considering environmental impact.

Conclusion Verification

When carbon emissions are treated as an evaluating criterion, several breakwater designs effectively balance environmental impact and functional performance. Suitable designs for wave height, durability, availability, water depth, and wave attenuation include MagnaDense Concrete, Concrete, Geopolymer Concrete, Rock, sediment blocks and geotubes (PP) with an armour layer. These materials meet the requirements, making them viable options for breakwater construction. However, geotubes made from polypropylene, are susceptible for degradation, causing microplastics to be released into the environment. For that reason, the geotubes are eliminated as well. Eventually, this leads to the most suitable breakwater designs, indicated in Table 6.15. However, it is already evident that while both concrete types and sediment blocks meet the 50-year durability requirement, there is a significant difference compared to rock. Rock is by far the material with the lowest emissions and offers a durability of 50 years.

Table 6.15: Summary of the Most Suitable Breakwater Designs

Breakwater Design Concept
MagnaDense Concrete
Concrete
Geopolymer Concrete
Rock
Rock & Concrete
Sediment Blocks

6.6. Evaluation and Selection of the best alternative

Following the initial requirements, most of the design concepts can be eliminated. What is left over, is presented in Table 6.15. In this section, these designs will be evaluated based on the defined criteria, including their weighting factors, shown in Table 5.13.

Scoring the Design Concepts per Criterion

Figure 6.6: Comparison Matrices

(a) Criterion: Ecosystem Impact

Ecosystem Impact	a	b	c	d	e	f	Total
a MD Concrete	1	1	1	1	1	1	6
b Concrete	1	1	1	1	1	1	6
c Geopolymer Concrete	1	1	1	1	1	1	6
d RM Rock	1	1	1	1	1	1	6
e RM Rock & Concrete	1	1	1	1	1	1	6
f Sediment Blocks	1	1	1	1	1	1	6

(b) Criterion: Robustness

Robustness	a	b	c	d	e	f	Total
a MD Concrete	1	1	1	1	1	2	6
b Concrete	1	1	1	1	1	2	6
c Geopolymer Concrete	1	1	1	1	1	2	6
d RM Rock	1	1	1	1	1	2	6
e RM Rock & Concrete	1	1	1	1	1	2	6
f Sediment Blocks	1/2	1/2	1/2	1/2	1/2	1	3.5

(c) Criterion: Local Availability

Local Availability	a	b	c	d	e	f	Total
a MD Concrete	1	1/2	1/2	1/2	1/2	1/3	3.33
b Concrete	2	1	1	1	1	1/2	6.5
c Geopolymer Concrete	2	1	1	1	1	1/2	6.5
d RM Rock	2	1	1	1	1	1/2	6.5
e RM Rock & Concrete	2	1	1	1	1	1/2	6.5
f Sediment Blocks	3	2	2	2	2	1/2	11.5

(d) Criterion: Energy Efficiency

Energy Efficiency	a	b	c	d	e	f	Total
a MD Concrete	1	1/2	1/2	1/2	1/2	1/2	3.5
b Concrete	2	1	1	1	1	1	7
c Geopolymer Concrete	2	1	1	1	1	1	7
d RM Rock	2	1	1	1	1	1	7
e RM Rock & Concrete	2	1	1	1	1	1	7
f Sediment Blocks	2	1	1	1	1	1	7

(e) Criterion: End-of-Life Planning

EoL Planning	a	b	c	d	e	f	Total
a MD Concrete	1	1	2	2	2	1	9
b Concrete	1	1	2	2	2	1	9
c Geopolymer Concrete	1/2	1/2	1	1	1	1/2	4.5
d RM Rock	1/2	1/2	1	1	1	1/2	4.5
e RM Rock & Concrete	1/2	1/2	1	1	1	1/2	4.5
f Sediment Blocks	1	1	2	2	2	1	9

(f) Criterion: Carbon Emissions

Carbon Emissions	a	b	c	d	e	f	Total
a MD Concrete	1	1/2	1/3	1/3	1/3	1/2	3
b Concrete	2	1	1/2	1/3	1/2	1	5.33
c Geopolymer Concrete	3	2	1	1/2	1	2	9.5
d RM Rock	3	3	2	1	2	3	14
e RM Rock & Concrete	3	2	1	1/2	1	2	9.5
f Sediment Blocks	2	1	1/2	1/3	1/2	1	5.33

Overall Ranking and Best Alternative

		RM Rock & Concrete		Sediment Blocks		RM Rock	
Criteria	WF	Score	SC * WF	Score	SC * WF	Score	SC * WF
Ecosystem Impact	0.127	6	0.762	6	0.762	6	0.762
Robustness	0.127	6	0.762	3.5	0.4445	6	0.762
Local Availability	0.196	6.5	1.274	11.5	2.254	6.5	1.274
Energy Efficiency	0.196	7	1.372	7	1.372	7	1.372
EoL Planning	0.077	4.5	0.3465	9	0.693	4.5	0.3465
Carbon Emissions	0.277	9.5	2.6315	5.33	1.47741	14	3.878
Total score			7.148		6.991		**8.395**

Table 6.16: Determination of the scores per alternative

		MD Concrete		Concrete		Geopolymer Concrete	
Criteria	WF	Score	SC * WF	Score	SC * WF	Score	SC * WF
Ecosystem Impact	0.127	6	0.762	6	0.762	6	0.762
Robustness	0.127	6	0.762	6	0.762	6	0.762
Local Availability	0.196	3.33	0.65268	6.5	1.274	6.5	1.274
Energy Efficiency	0.196	3.5	0.686	7	1.372	7	1.372
EoL Planning	0.077	9	0.693	9	0.693	4.5	0.3465
Carbon Emissions	0.277	3	0.831	5.33	1.47741	9.5	2.6315
Total score			4.387		6.340		7.148

Table 6.17: Determination of the scores per alternative

The evaluation of the most suitable breakwater design alternatives (MagnaDense Concrete, Concrete, Geopolymer Concrete, rubble mound Rock, rubble mound Rock & Concrete, and Sediment Blocks) has been conducted based on six evaluation criteria: Ecosystem Impact, Robustness, Local Availability, Energy Efficiency, End-of-Life (EoL) Planning, and Carbon Emissions. Each criterion is weighted according to its importance (Table 5.13d), and the scores for each alternative were calculated by multiplying the individual scores by their respective weights.

Among these alternatives, Tables 6.16 and 6.17 show that the rubble mound structure achieves the highest total score of 8.395, indicating its superiority in meeting the combined criteria. This high score suggests that this design is the most suitable alternative for a carbon-neutral breakwater design, in this specific case under these circumstances. It excels in balancing ecosystem impact, robustness, local availability, energy efficiency, end-of-life planning, and carbon emissions. The rubble mound rock design's higher score can be attributed to its better performance across multiple criteria, particularly in terms of carbon emissions, where it showed substantial savings.

In contrast, while MagnaDense Concrete has the lowest score, indicating it is the least suitable option due to its relatively poor performance in several criteria, particularly in carbon emissions. Although MagnaDense Concrete is highly durable, its environmental and economic drawbacks make it less favourable. Therefore, based on the comprehensive evaluation, the use of natural rock is recommended as the optimal choice for implementing a carbon-neutral breakwater design, ensuring a sustainable and effective solution for coastal protection.

Besides scoring high on the previously discussed criteria, the chosen design should be affordable. In Figure 6.7, the value and costs are compared. The design 'Rubble Mound Rock' is set as the reference, placed at the intersection of the quadrants, serving as the benchmark. The analysis reveals that there are no designs in Quadrant I, indicating that no design offers both lower cost and higher value relative to Rubble Mound Rock. Notably, all other designs fall into Quadrant III, suggesting that while they have slightly lower value compared to Rubble Mound Rock, they also come with higher costs. Consequently, Rubble Mound Rock remains the best option, balancing value and affordability effectively.

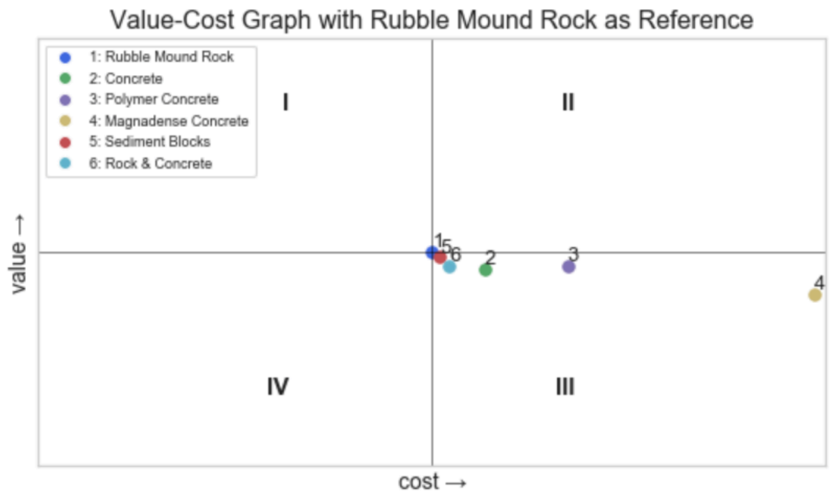


Figure 6.7: Value-Cost Graph of the Alternatives

6.7. Final Design Selection

A breakwater consisting of rubble mound rock emerged as the most suitable option based on the boundary conditions, requirements, and evaluation criteria. This design concept will be further developed in this section. Given the presence of soft subsoil and the substantial weight of the rubble mound breakwater, the implementation of a fascine mattress is necessary to prevent excessive settlement. The fascine mattress, constructed from bundles of brushwood or other flexible materials, will provide a stable foundation for the heavy breakwater. It distributes the load more evenly across the soft subsoil, reducing the risk of differential settlement and enhancing the overall stability of the structure. The required gradation of the armour stone for the breakwater was determined using the Van der Meer (1988) formula. This formula is developed for conditions without depth-induced wave breaking, which is valid for the present application (significant waves smaller than 0.42 m in a water depth of about 3 m). Furthermore, this formula considers factors such as wave conditions, slope stability, and stone size to ensure adequate protection and durability of the breakwater. The Van der Meer (1988) equation is an approach for designing rubble mound structures in relatively deep water (without depth-induced wave breaking), ensuring that the chosen materials and construction techniques will withstand the harsh marine environment and provide long-term coastal protection. However, it should be noted, that more recent and improved formulae exists, especially for breakwaters in relatively shallow water (conditions with wave breaking prior to waves reaching the structure), but for this preliminary design, these equations suffice.

To design the armour layer, the Van der Meer method (1988) is used. For the determination of the nominal diameter D_{n50}, the transition parameter needs to be determined first by means of the following equation:

$$\xi_{transition} = [\frac{c_{pl}}{c_s} P^{0.31} \sqrt{\tan\alpha}]^{\frac{1}{P+0.5}} \tag{6.1}$$

In which:

- $\xi_{transition}$, transition parameter
- c_{pl}, the plunging coefficient (6.2)
- c_s, the surging coefficient (1)
- P, the permeability parameter (0.1 = impermeable core);
- α, the slope angle

Depending on the breaker parameter, either equation 6.2 or 6.3 needs to be used. In the case of a slope gentler than 1:4, equation 6.2 should be used irrespective of the value of the breaker parameter.

Equation 6.2 is used in the case of plunging waves ($\xi_{s-1.0} < \xi_{transition}$)

$$\frac{H_s}{\triangle D_{n50}} = 6.2P^{0.18}(\frac{S_d}{\sqrt{N}})^{0.2}(\xi_{s-1.0})^{-0.5} \tag{6.2}$$

Equation 6.3 is used in the case of surging waves ($\xi_{s-1.0} \geq \xi_{transition}$)

$$\frac{H_s}{\triangle D_{n50}} = 1.0P^{-0.13}(\frac{S_d}{\sqrt{N}})^{0.2}\sqrt{\cot\alpha}(\xi_{s-1.0})^{P} \tag{6.3}$$

In which:

- D_{n50} nominal diameter [m];
- H_s, significant wave height [m];
- N, number of waves [-];
- S, damage level of the structure [-];
- $\triangle$, relative density of the armour layer ($\frac{\rho_{armour}-\rho_{water}}{\rho_{water}}$) [-];
- ρ_{armour}, material density of armour layer [kg/m^3];
- ρ_{water}, water density [kg/m^3];

Input Parameters

To design an effective breakwater, several input parameters need to be considered. These parameters include wave characteristics, material properties, and geometric specifications of the breakwater. The following tables summarize the input parameters used in this design for deep water conditions:

Symbol	Value	Unity	Description
H_s	0,42	[m]	Significant wave height
T_m	2,22	[s]	Mean wave period (0.85*T_p)
N	7500	[-]	Number of waves
ρ_{water}	1000	[kg/m^3]	Density of fresh water
ρ_{rock}	2600	[kg/m^3]	Density of rock
Δ	1,60	[-]	Relative density
S_d	2	[m]	Damage level (no damage)
P	0.5	[-]	Permeability (wave dissipation)
cot(α)	2	[-]	Slope of the breakwater, given as 1:m
BL	-3	[m + CD]	Bed level
c_{pl}	6.2	[-]	Coefficient for plunging breakers
c_s	1	[-]	Coefficient for surging breakers

Table 6.18: Table data for wave and rock parameters.

Table 6.18 shows the parameters that are used for the calculation of the breakwater. The number of waves is set to be 7500, because for larger number of waves the armour layer is considered to have reached an equilibrium. Similarly, the damage coefficient, S_d, is considered to be 2 (which is often used for design purposes). Because of the mild wave conditions, only minor damage is assumed to be acceptable (CIRIA et al., 2007). The core of the breakwater will consist of aggregates and therefore, the notional permeability will be equal to 0.5 according to Van der Meer (1988).

Resulting Design Parameters

Table 6.19 summarizes the calculated design parameters for the breakwater:

Result			
Symbol	**Value**	**Unity**	**Description**
$\xi_{\text{transition}}$	3.54	[-]	Transition value for breaker parameter
ξ_m	2.14	[-]	Breaker parameter
Breaker type:		plunging	
S_d	2.00	[-]	Damage level
$\frac{H_s}{\Delta D_{n50}}$	1.76	[-]	Stability number
D_{n50}	0.15	[m]	Nominal stone diameter
Grading		LM_A 5-40	
D_{n50}	0.12	[m]	Reduced Nominal stone diameter (CL<WL, 0.8D_{n50})
Grading		CP90/250	

Table 6.19: Table data for stone parameters (Figure C.4)

According to this, the armour layer needs to be at least 30 cm thick, when the crest level exceeds the water level. The layer could be thinner when the crest level is below water level. The armour layer can be optimized when the breakwater is low-crested. The nominal diameter can be reduced by 20%. This results in a stone diameter of 0.12 m and consequently an armour layer of no less than 0.24 m. Furthermore, the core will consist of aggregates.

Toe and Foundation

The toe is often constructed to support the lower part of the armour layer. On top of that, they can be applied in order to prevent scour development near the structure. A supplemental function of constructing a toe, is to keep the armour units in its place without any chance of sliding. The width of the toe should be at least 3*D_{n50} or in case of a very small armour gradation and practical reasons, at least 2 meters (CIRIA et al., 2007). In this case, the toe will be designed with a width of 2 meters.

The foundation of the structure will consist of a fascine mattress. The usual thickness is around 0.5 meters, which will also be assumed in this case, as the loads will not be extremely high (Van Aalsburg, 2024).

Breakwater Design

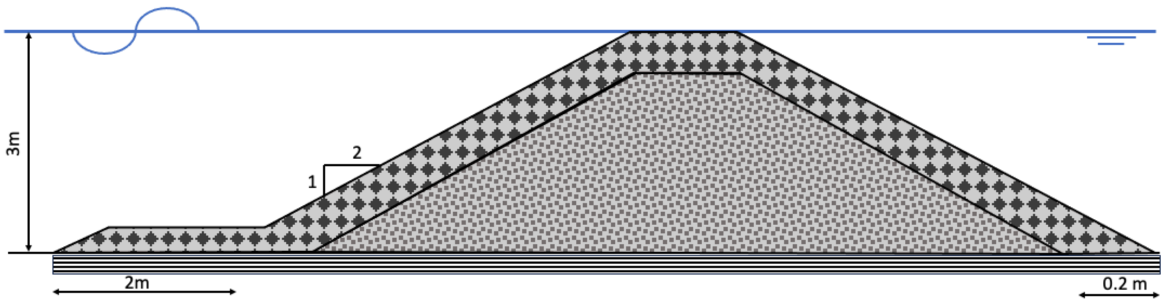


Figure 6.8: Rubble mound design

To minimize the amount of material required, a low-crested breakwater is selected. Designing a low-crested rubble mound breakwater for a water depth of 3 meters, starts by ensuring the transmission coefficient (K_t) does not exceed 0.47, given the wave height (H_i) of 0.42 meters and the maximum allowed wave height behind the structure (H_t) of 0.2 meters. Using the graph (Figures 5.12a and 5.12b), we estimate the relative crest freeboard (R_c/H_i) for $K_t = 0.47$ to be around 0 meters below water level. Indicating the crest of the breakwater is at the water surface.
The breakwater design includes:

- A crest width of 3 meters
- Side slopes of 1:2 (vertical:horizontal)
- A toe length of 2 meters for stability

The resulting structure is given in Figure 6.8 and the associated carbon emissions are given in Table 6.20. In Figure C.6, the carbon emissions calculated with DuboCalc are shown. The carbon sequestration potential of the fascine mattress is included in Table 6.20, but it is not assumed to be part of the breakwater construction. This is due to the fact that a fascine mattress is not typically a standard component of breakwater designs. However, its inclusion could be an effective and straightforward addition to achieve carbon neutrality. For the calculation of the related carbon emissions of the fascine mattress under the complete length of the structure, it is assumed that the bundles consist of 70% solid brushwood and 30% air and water.

Table 6.20: Overview of CO_2 emission/storage per component of the rubble mound structure

What	Quantity	NMD		DuboCalc		EcoInvent (Limestone)	
		kg CO_2/m^3	ton CO_2	kg CO_2/m^3	ton CO_2	kg CO_2/m^3	ton CO_2
Rubble Stone Core	21904 m^3	31.14	682.1	37.86	829.3	34.0	744.7
Rubble Stone Armour Layer	3966 m^3	22.26	88.3	30.7	121.8	34.0	134.8
CO_2 storage by willow branches (Fascine Mattress)	7150.5 m^3	-92	-658	2.84	40.5	N/A	N/A
Total CO_2 emission (Excluding storage in fascine mattress)			**770.4**		**951.2**		**879.6**
Total CO_2 emission (Including storage in fascine mattress)			**112.4**		**991.7**		**N/A**

Table 6.20, presents carbon emissions calculated using data straight from the NMD, data from the tool DuboCalc, as well as data from EcoInvent. Remarkably, the total carbon emissions calculated using NMD data show lower emissions for both the core and the armour layer compared to the data from DuboCalc. This difference suggests that the data provided in DuboCalc may not be up to date, resulting in an overestimation of the carbon footprint. Additionally, DuboCalc does not account for any carbon sequestration by materials such as brushwood, which leads to a larger carbon footprint for the fascine mattress and no credit for carbon storage.

In contrast, EcoInvent, although including a wider range of data, it does not include the specific rubble rock used in hydraulic engineering as detailed in the NMD. Instead, it includes limestone, which is used in this case for comparison purposes. Furthermore, EcoInvent does not contain data on fascine mattresses; therefore, these values are not included in the table. Although using outdated data, this suggests that DuboCalc provides a more accurate calculation of the carbon footprint of breakwaters compared to SimaPro, which uses EcoInvent. In addition, due to the lack of updates, carbon footprint calculations are often performed using personal tools that can load the latest data, ensuring a more accurate assessment of the carbon footprint.

From Table 6.20, it can be concluded that the core material contributes the most to the total carbon emissions of the breakwater due to the large volume required. Therefore, different configurations are proposed to address this issue. Multiple choices can be made concerning the core material, like sand and clay. The carbon emissions associated with using sand as core material can be seen in Table 6.22. However, this design uses blast furnace slag in the core, which can be seen in Table 6.21. Interestingly, this component generates minimal to zero carbon emissions, making it a more favorable option compared to using sand. Blast furnace slag, a by-product, achieved from steel production, currently is not accounted for any carbon emissions, highlighting its potential as an environmentally favourable material for breakwater construction. However, upcoming regulatory changes are expected to negatively impact the carbon emissions associated with blast furnace slag. The total CO_2 emissions calculation without the fascine mattress shows that the rubble stone armour layer contributes 88.3 tons of CO_2. However, if the fascine mattress were included, the overall carbon footprint would be substantially reduced by its sequestration of 658 tons of CO_2, potentially resulting in a net negative carbon impact. This implies that including the fascine mattress could not only neutralize the emissions but also provide a net environmental benefit.

Table 6.21: Overview of CO_2 emission/storage per component of the rubble mound structure with a slag as core

What	Quantity	kg CO_2/m^3	ton CO_2	DuboCalc ($kgCO_2/m^3$)
Blast Furnace Slag Core	21904 m^3	0	0	0
Rubble Stone Armour layer	3966 m^3	22.26	88.3	121.8
CO_2 storage by willow branches (Fascine Mattress)	7150.5 m^3	-92	-658	40.5
Total CO_2 emission (Excluding storage in fascine mattress)			**88.3**	**121.8**
Total CO_2 emission (Including storage in fascine mattress)			**-569.7**	**162.3**

Table 6.22: Overview of CO_2 emission/storage per component of the rubble mound structure with a sand as core

What	Quantity	$kgCO_2/m^3$	ton CO_2	DuboCalc ($kgCO_2/m^3$)
Sand	21904 m^3	15.76	345.28	345.28
Rubble Stone Armour layer	3966 m^3	22.26	88.3	121.8
CO_2 storage by willow branches (Fascine Mattress)	7150.5 m^3	-92	-658	40.5
Total CO_2 emission (Excluding storage in fascine mattress)			**433.6**	**467.1**
Total CO_2 emission (Including storage in fascine mattress)			**-224.4**	**507.6**

6.8. Sensitivity Analysis

6.8.1. Introduction

Concerning the current requirements and boundary conditions, it is currently not yet possible to construct a carbon neutral breakwater. This section introduces the need for a comprehensive sensitivity analysis to explore alternative scenarios and identify the most impactful strategies for reducing carbon emissions. By critically examining the key assumptions related to material choices, production processes, and end-of-life planning, we aim to create a pathway toward a CO_2-neutral breakwater. The primary assumptions examined include the lifespan of the breakwater, boundary conditions, and shifts in weight factors.

6.8.2. Material Choice and Durability

The most significant bottleneck is associated with material choice and the stringent requirements linked to it. Striking a balance between long-term durability and low carbon emissions proves challenging, as highly durable materials typically exhibit higher carbon footprints. The expected lifetime of a breakwater and the durability of its materials are important aspects, given that these structures are often intended as permanent fixtures, requiring materials that do not degrade substantially over time. The starting assumption for the structure's durability is 50 years.

However, reducing this expected durability to 40 years, as illustrated in Figure 6.3, could allow for the use of brushwood mattresses, that sequestrate carbon, consequently having carbon emissions below 0 $kgCO_2/m^3$. This reduction in durability might necessitate additional maintenance and regular monitoring. Moreover, in a scenario where durability is disregarded entirely, the impact on the outcome would be even larger, presenting a broader range of options. However, this scenario would also place greater emphasis on energy intensity due to increased maintenance needs, and on end-of-life planning, as materials could be repurposed. Under these conditions, materials like softwood, hardwood, and bamboo become favourable, with hardwood particularly advantageous if evaluated according to the new set A2. Additionally, biodegradable geotextile tubes made from jute emerge as viable options.

Assuming the use of fully electric or hydrogen-driven (emission-free) transport and construction methods does not significantly alter the outcome, maintaining rock as the most suitable option (in the scenario of an expected lifetime of 50 years). This scenario underscores the inherent robustness and environmental compatibility of rock, even under adjusted energy assumptions.

6.8.3. Wave Height and Boundary Conditions

Another critical factor is the boundary condition related to wave height. The possibility of constructing a carbon-neutral breakwater significantly depends on this variable. For instance, with a wave height of 0.42 meters, it is feasible to construct a carbon-neutral breakwater, depending on the required lifetime of the structure. Brushwood grids, can withstand wave heights up to approximately 3 meters. This represents the highest wave height achievable using carbon-neutral or carbon-negative materials, according to Figure 6.2.

Therefore, when designing a carbon-neutral breakwater, these constraints must be considered. Brushwood can be used effectively up to wave heights of 3 meters, offering a sustainable solution. In contrast, for other materials, the design must account for the reduced durability of brushwood, limiting the wave height to 2 meters to ensure the breakwater's integrity and longevity. This indicates the effect wave climate can have on the carbon emissions of a breakwater. It highlights the trade-offs between achieving carbon neutrality and meeting structural performance requirements, emphasizing the importance of selecting appropriate materials based on the specific environmental conditions and projected lifespan of the breakwater.

6.8.4. Evaluation Criteria

The importance given to different evaluation criteria can greatly affect the results. However, the the final design is not that sensible for those changes. Some scenarios are examined. For instance, if we prioritize both carbon emissions and robustness equally, the most suitable materials include RM Rock, Geopolymer Concrete, and Sediment Blocks, although the latter scores lower due to its robustness. Conversely, if carbon emissions and end-of-life planning are prioritized equally, RM Rock still leads but with a smaller margin, and Geopolymer Concrete and Concrete show significant improvements due to their good end-of-life planning practices.

This highlights how critical these criteria are in the overall evaluation. Materials that balance these high-priority factors are more likely to be chosen. This shows that it's crucial to carefully decide and justify how much weight each criterion should have to ensure the evaluation aligns with the project's environmental and practical goals.

6.8.5. Calculation Tools

The use of calculation tools like DuboCalc and EcoInvent significantly impacts the outcome. DuboCalc, despite using outdated data, provides a more accurate calculation of the carbon footprint for breakwaters compared to SimaPro, which uses EcoInvent. DuboCalc's higher carbon footprint estimates are mainly due to its omission of carbon sequestration potential in materials such as brushwood. On the other hand, EcoInvent includes natural rock like limestone but lacks specific data on hydraulic engineering materials and fascine mattresses, making its estimates less tailored for this specific application. Therefore, using personal tools that can load the latest data often provides a more accurate carbon footprint calculation.

6.8.6. Carbon Sequestration Potential

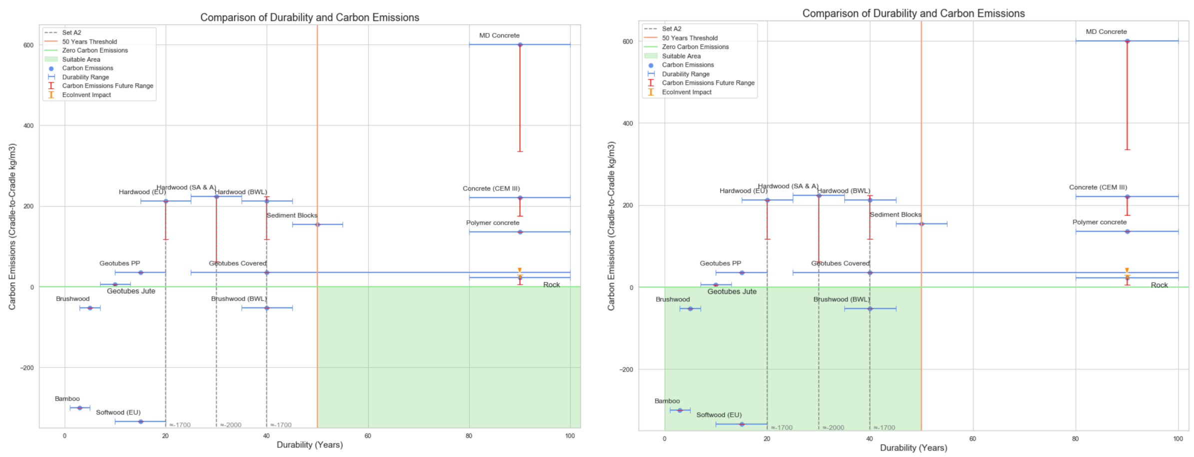
The decision to include or exclude the carbon sequestration potential of the fascine mattress is another crucial aspect. Table 6.20, shows that incorporating the fascine mattress significantly reduces the overall carbon footprint of the breakwater structure. Without the fascine mattress, the total CO_2 emissions amount to 770.4 tons. Including it reduces the total emissions to 112.4 tons. The carbon sequestration capability of the fascine mattress is significant, and its inclusion can move the breakwater closer to carbon neutrality. However, since a fascine mattress is not a standard component, this decision should be made based on specific project goals and environmental conditions.

6.8.7. Conclusion

In conclusion, adjusting assumptions about the lifespan, boundary conditions, and weight factors can significantly impact the choice of materials and the overall feasibility of building a carbon-neutral breakwater. By exploring these assumptions, we can find more sustainable and environmentally friendly designs, balancing functionality with ecological responsibility.

6.9. Carbon Neutral Breakwater Scenario

In this section, a different concession is made: the initial required lifetime has been removed as a requirement. However, the structure must still meet the requirement of achieving carbon neutrality. This adjustment leads to explore a different range of options, as illustrated in Figure 6.9b. This broader scope allows for the inclusion of additional materials that can be utilized in designing a carbon-neutral breakwater.



(a) (b)

Figure 6.9: The search area under certain conditions

Eventually, the design is based on the scenario that the expected lifetime of the breakwater is not 50 years anymore. This means that brushwood becomes an available option. Figure 6.10 shows a simple sketch of the design, constructed from brushwood. The brushwood can be applied in different configurations.

The other configuration is indicated in Appendix C. This configuration, in Figure 6.10, is using only brushwood bound into grids and filled up with local dredged material, up to the water level, with reed planted on top for additional damping of the waves and create a construction that becomes part of the environment. The other configuration is similar with an armour layer of rock. This is added to provide additional durability and protection against storms. For the calculation of the related carbon emissions of the structure, the diameter of the bundle is taken at 15 cm and the grids at 1x1 m. Table 6.23 outlines the carbon emissions associated with this design. The data indicates that constructing a carbon-neutral breakwater is feasible under these conditions.

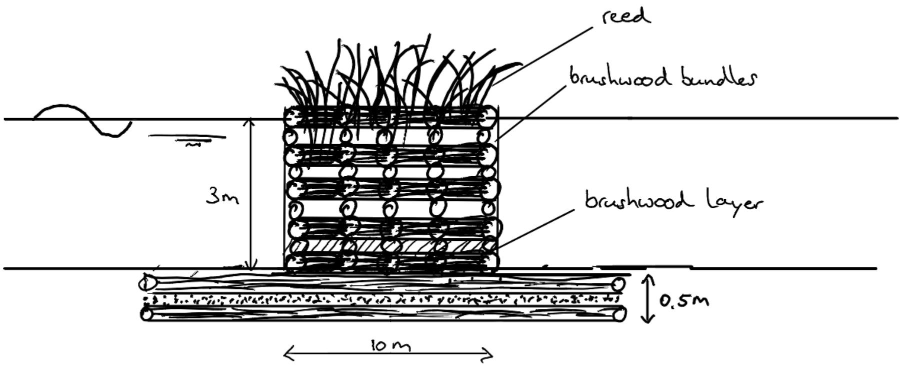


Figure 6.10: Brushwood grids configuration with reed

The proposed design features a constructed land strip, a type of peat ridge, designed to function effectively in a water depth of 3 meters. The structure spans a total width of about 10 meters. The land strip, which forms the core of the structure is 3 meters high. Constructed from layers of compacted peat and soil, the land strip provides a stable, raised area just above or at the water level. This foundational element ensures the overall stability of the structure and serves as a platform for additional protective layers. Additionally, a biodegradable maize cloth is placed on the sides of the landmass to prevent the runoff of peat sludge.

On top of the created land strip, reed are planted. These banks are composed of densely planted reeds and associated soil. They enhance the stability of the entire structure by dissipating wave energy and reducing erosion. Additionally, the reed banks contribute to the ecological value of the area by providing habitat for wildlife, integrating natural vegetation into the design for both structural and environmental benefits. The bundles, made from willow branches, are another crucial component of the design. These bundles have a diameter of 10-15cm and are created using a machine that presses and ties the branches together with sisal rope. Positioned in a grid system, the bundles form a flexible, durable mesh layer that reinforces the land strip and reed banks. This mesh helps distribute loads and resist movement, maintaining the structural integrity of the land strip. Reed mats and sisal twine secure the willow bundles, adding cohesion and erosion protection. A fascine mattress, a flexible mat filled with local soil, anchors the structure to the peat layer, preventing movement and ensuring a stable foundation. Construction involves placing the fascine mattress, building the land strip with peat and soil, creating reed banks, installing willow bundles in a grid, and securing with reed mats and twine. The structure should be inspected and adjusted for stability and alignment. The brushwood located at water level or just above is prone to quick degradation. Regular monitoring is required in order to make sure the breakwater maintains its structural stability and height.

6.10. Concluding Remarks

In conclusion, verifying various breakwater designs underscores the challenge of balancing durability, environmental impact, and functional performance. The rubble mound rock design emerged as the most suitable option, excelling in ecosystem impact, robustness, local availability, energy efficiency, and end-of-life planning. However, this design does not meet the criteria for a carbon-neutral breakwater, even when considering the carbon sequestration of the brushwood used in the fascine mattress. While using a larger fascine mattress could potentially achieve carbon neutrality, it is not its intended purpose.

Table 6.23: Overview of CO_2 emission/storage per component of breakwater with brushwood grids and reed

What	Quantity	Unit	kg CO_2/m^3	ton CO_2	DuboCalc
Willow branches stacked	10603	m^3	-92	-975.5	60.14
Dredging material to fill grids	34397	m^3	0.98	33.7	44.03
Willow branches in fascine mattress	5250	m^3	-92	-483	42.5
Total CO_2 emission (Excluding storage in fascine mattress)				**-941.8**	**104.17**
Total CO_2 emission (Including storage in fascine mattress)				**-1424.8**	**146.71**

Utilizing blast furnace slag as a core material could offer a solution to achieve carbon neutrality while still using armour rock, making it a sustainable and effective option for coastal protection. However, trade-offs remain, as no single material perfectly satisfies all requirements. Achieving carbon neutrality will likely require concessions in the requirements. For instance, reducing the lifetime of the breakwater can allow the use of more sustainable materials like brushwood grids, which sequester carbon but have a shorter lifespan. Future designs must continue to explore innovative materials and methods to enhance sustainability while maintaining structural integrity, potentially revisiting and adjusting initial criteria to meet environmental goals effectively.

7 Discussion

The primary objective of this thesis is to explore how an integrated approach can effectively tackle the challenges posed by achieving carbon neutrality in breakwater construction, while ensuring project feasibility and sustainability. The results support the hypothesis that a comprehensive approach, considering technical, environmental, and operational aspects, is essential for optimizing sustainability in breakwater projects. This finding aligns with previous research by Broekens et al. (Broekens et al., 2011) and Saravia de Los Reyes et al. (Saravia de los Reyes et al., 2020), underscoring the importance of life-cycle assessments and sustainable material selection in reducing carbon emissions.

7.1. Interpretation of the results

Rock is identified as the best material for breakwater construction in mild wave climates, such as the Braassemermeer, especially for projects with a lifespan of over 50 years and a focus on minimizing carbon emissions. Alternatives like sediment blocks, geopolymer concrete, and regular concrete have significantly higher carbon footprints, up to 10 times that of rock, primarily due to cement use. MagnaDense has an even larger carbon footprint, over 20 times that of rock.

It should be noted that this research has focused on transport distance and volume. However, by achieving higher density per armour unit, using MagnaDense for example, the size of each armour unit can be reduced, which in turn lowers the CO_2 emissions per block. This potential benefit increases when blocks are produced locally, a factor not fully accounted for in the study. This can be achieved by using alternative aggregates with higher densities or by reusing materials that can be sourced nearby. Examples include using blast furnace slag, though it is uncertain how beneficial this will remain, as CO_2 emissions from this material might also be regulated in the near future. There is still potential for gains in this area, particularly with higher density materials and recycling.

Holding on to the 50 years lifetime requirement a potential solution is using fascine mattresses constructed from brushwood, which sequesters carbon, underneath the structure to offset the carbon emissions from the rest of the structure. The fascine mattresses are primarily used for stability concerns of the breakwater, but the size can be extended for additional carbon sequestration. While this method shows promise, it raises concerns; growing and harvesting brushwood solely for carbon sequestration without serving additional functions should considered thoroughly. Therefore, while possible, achieving carbon neutrality requires careful consideration of both environmental impact and practicality.

The results indicate that achieving carbon neutrality requires trade-offs, such as balancing durability with low emissions. For instance, reducing the typical 50-year lifespan requirement could allow for carbon-sequestering materials like brushwood mattresses, although this increases maintenance needs. Removing durability constraints expands material options but necessitates careful end-of-life planning. Materials like softwood, hardwood, bamboo, and jute-based biodegradable geotextile tubes become viable, with hardwood being particularly beneficial under revised criteria.

For environments with wave heights above 5 meters, the use of cement-based materials is currently unavoidable due to their unmatched stability. Currently, no low-carbon material offers the necessary durability and structural integrity to withstand such high-energy conditions. Therefore, the focus should shift towards making the production of concrete carbon-neutral. This could involve innovative production techniques, such as using incorporating carbon capture and storage technologies to offset carbon emissions.

Moreover, DuboCalc and SimaPro are effective quantification tools of carbon emissions. DuboCalc includes the complete process for fascine mattresses but lacks customization options for specifications like thickness. In contrast, SimaPro uses the EcoInvent database, enabling detailed modifications and process analyses. While SimaPro performs similar calculations, DuboCalcs focus on hydraulic construction makes it particularly useful, with specific data on rubble stone and brushwood, which SimaPro lacks due to its broader focus. This specificity makes DuboCalc efficient for initial carbon footprint assessments in hydraulic constructions despite its limitations in material and process customization.

The differences in results between EcoInvent and NMD data arise from scope and data specificity. EcoInvent offers a global perspective with detailed datasets, leading to more accurate environmental impact assessments. In contrast, NMD is region-specific and may not reflect the latest global data, causing significant variations in carbon footprint results. This discrepancy highlights the importance of selecting appropriate data sources depending on the project's geographical and material-specific contexts.

To improve DuboCalc, enhancements should focus on phases A4 and A5 by incorporating specific, up-todate transport distances and methods. Including carbon sequestration in phases A1 to A3, particularly for materials like timber with high sequestration potential, can significantly impact overall carbon assessments. While DuboCalc remains user-friendly for standard projects, integrating flexible and detailed data from sources like EcoInvent and enabling customization in transport and construction processes will improve its accuracy. Updating the NMD to reflect current global data and including carbon sequestration will bridge the gap between DuboCalc and SimaPro, ensuring more reliable and comprehensive environmental assessments.

Furthermore, transitioning to electric and hydrogen-powered machinery has the potential to significantly reduce emissions during breakwater construction, as indicated by the research findings. However, the analysis reveals several critical challenges that need to be addressed. High initial costs and technological limitations currently impede widespread adoption. Moreover, the lack of robust charging and refueling infrastructure, along with issues related to hydrogen storage and safety, complicates the transition process. These findings suggest that the construction industry must overcome these barriers to fully leverage the benefits of these technologies.

The implications of these results are significant. For instance, without adequate infrastructure, the shift to low-emission machinery cannot be effectively realized, limiting the potential reduction in construction-related emissions. The preference for familiar technologies over new, eco-friendly alternatives indicates a need for stronger incentives and support to encourage companies to adopt these innovations. Additionally, the study highlights that while switching to sustainable fuels can reduce emissions associated with transportation, the inherent carbon footprint of traditional construction materials like concrete and steel remains a substantial issue.

Thus, the findings suggest a need for a comprehensive strategy that not only focuses on adopting low-emission machinery but also emphasizes the use of low-carbon materials. The research indicates that integrating low-carbon materials, such as geopolymer concrete or bamboo, alongside sustainable transportation methods, can more effectively reduce the overall environmental impact of breakwater construction. This approach addresses both production and transportation emissions, offering a more integrated solution to achieving CO_2-neutral breakwater projects.

The primary challenge in constructing a CO_2-neutral breakwater lies in selecting materials that balance durability with minimal carbon emissions. Traditional materials like rock, while durable, have a positive carbon footprint due to extraction and transport. Alternatives like brushwood mattresses, softwood, hardwood, and bamboo offer lower carbon emissions and potential carbon sequestration benefits but lack the same durability and require more maintenance. This trade-off is especially evident with wave height constraints, as brushwood can handle waves up to 3 meters but is less effective in more turbulent conditions. Conversely, materials like rock, despite their higher carbon footprint, remain the best option for handling higher wave conditions due to their durability.

7.2. Research Limitations

The limitations of this research are primarily related to the availability and accuracy of data, the scope of material evaluation, and the practical applicability of findings. Firstly, the reliance on existing databases and literature for carbon footprint calculations means that some data may be outdated or not fully representative of current practices. To address this, the data sources used should be continuously updated and validated. Collaborating with industry stakeholders to obtain the latest information and incorporating real-time data collection methods could significantly improve the accuracy of carbon footprint assessments. Additionally, developing a standardized framework for updating carbon footprint databases could ensure that the data remains current and relevant.

Additionally, the research primarily focuses on a limited range of materials and does not comprehensively cover all potential sustainable alternatives or innovative technologies that could be explored. Expanding the scope of material evaluation to include a broader spectrum of sustainable options and emerging technologies is crucial. Future studies should investigate novel materials, such as bio-based composites or recycled materials like HDPE, and assess their viability in breakwater construction.

The study also does not take into account the indirect emissions associated with the full life-cycle of materials and construction equipment, such as those from manufacturing equipment and supply chain logistics, which could affect the overall carbon footprint assessment. Integrating life-cycle assessment (LCA) methodologies of these indirect processes can provide a more comprehensive analysis by quantifying these emissions.

Practical constraints, such as scalability and economic feasibility of using alternative materials, are also not fully addressed. Pilot projects and case studies are necessary to test these aspects. Engaging with policymakers and industry leaders to explore funding and incentives can drive the adoption of low-carbon options. Conducting cost-benefit analyses that consider long-term savings from reduced maintenance and enhanced durability of sustainable materials can support their implementation.

Furthermore, the research's assumptions regarding the long-term performance and durability of alternative materials, like geopolymer concrete en sediment blocks, under diverse environmental conditions require further validation through extensive field testing and long-term monitoring. Collaboration with academic institutions and industry partners can support this effort. These limitations suggest a need for ongoing research and real-world experiments to refine the findings and ensure their broader applicability and reliability.

7.3. Critical Reflection

Reflecting critically on the research process reveals several key areas for improvement, particularly regarding the depth of inquiry during interviews and the limitations of available data. The interviews could have benefited from more pointed questions that directly addressed the practical challenges and feasibility of using various materials in breakwater construction. For example, diving deeper into the long-term maintenance needs and real-world performance of alternative materials like brushwood and biodegradable geotextiles might have provided more nuanced insights. Furthermore, upon reviewing the methodology, it could be improved by incorporating steps that explore research possibilities. This includes identifying and testing emerging materials like bio-based composites and recycled materials. Collaborating with research institutions to investigate new engineering techniques could also enhance sustainability and efficiency. Integrating these research possibilities into the design process would not only expand the range of viable materials but also ensure that the latest advancements in sustainable construction are considered. This would provide a more comprehensive and forward-thinking approach to achieving carbon-neutral breakwater designs.

Additionally, the reliance on existing databases like NMD and EcoInvent, which may contain outdated or incomplete data, presents a significant limitation. These tools often lack specific information on innovative materials and construction techniques for hydraulic engineering projects. Moreover, due to time constraints and lack of licenses, research using SimaPro was not conducted, limiting comparability with DuboCalc. To address this, more comprehensive and up-to-date datasets are needed, along with a broader range of case studies and real-world applications. A more thorough approach, including hands-on use of SimaPro, would enhance the accuracy and applicability of the research findings.

8 Conclusions

This thesis investigates the feasibility of achieving carbon-neutral breakwater construction by integrating sustainable materials, innovative design approaches, and advanced carbon quantification tools. The primary goal is to balance the need for robust coastal protection with minimizing environmental impact, aligning with global climate change mitigation efforts. Consequently, leading to the following research question:

How can an integrated approach effectively tackle the challenges posed by achieving carbon neutrality in breakwater construction, while ensuring project feasibility and sustainability?

To answer this question the sub-questions that were introduced in chapter 1 are repeated and answered.

Sub-question 1: What tools are available to quantify the carbon emissions of breakwaters and what are the limitations and how can these be mitigated?
DuboCalc and SimaPro serve as crucial tools for assessing carbon emissions in breakwater projects, each with specific advantages and drawbacks. DuboCalc offers ease of use and detailed data for Dutch construction projects but makes use of outdated data and lacks features like carbon sequestration and flexible transport distance calculations. SimaPro provides comprehensive life-cycle assessments with a broad database, though its complexity and time-consuming nature limit accessibility, and it lacks focus on hydraulic construction materials, like fascine mattresses, and it does not include carbon sequestration. To improve these tools, updating databases, integrating carbon sequestration capabilities, and enhancing usability and customization options are essential. These enhancements will ensure that both tools provide more accurate, flexible, and comprehensive environmental assessments, ultimately supporting more sustainable construction practices. That said, DuboCalc remains the most suitable option for now. Despite its limitations in specific data and carbon sequestration, its focus on construction projects makes it user-friendly and effective for estimating carbon emissions for breakwaters.

Sub-question 2: How can emissions due to transportation and construction equipment be reduced?
To reduce emissions in transport, using biofuels can significantly lower greenhouse gas emissions, with the volume of transported materials having a more pronounced effect on the carbon footprint than distance. However, biofuels are not entirely carbon-neutral due to emissions from processing, and challenges remain with production capacity and the high costs. Hydrogen and battery electric vehicles (BEVs) can provide carbon neutrality in transport, but regulations concerning hydrogen storage make it challenging. Additionally, hydrogen in maritime transport is difficult due to the storage limitations and safety risk on a ship. Achieving full carbon neutrality requires comprehensive efforts to offset or eliminate emissions throughout the biofuel supply chain. This involves not only adopting biofuels but also ensuring efficient fuel usage and optimized transport logistics, such as improved fuel availability and the establishment of fuel stations. Efficient fuel storage, including advancements in volumetric energy density, will support the widespread use of hydrogen and battery electric vehicles (BEVs).

In construction, electric and hydrogen fuel cell machinery can reduce carbon footprints to zero onsite, making them viable for small to medium-sized projects, or where downtime can be accommodated. The primary limitations include high initial costs, unfamiliarity with these alternative technologies, strict regulations on hydrogen storage, and limited availability of power stations for electric machinery. Addressing these limitations through infrastructure development and regulatory adjustments is key to broader adoption and effectiveness in reducing emissions. Additionally, requirements need to be set to use carbon neutral material in order to drive research on energy efficiency and charging facilities.

Sub-question 3: What materials can be identified and optimized for use in breakwater construction to minimize carbon emissions, ensuring both stability and water safety?
In breakwater construction, using materials such as rock and low-carbon alternatives like brushwood grids and timber can reduce carbon emissions while maintaining stability and water safety. When holding on to a lifetime of 50 years, rock, although not completely carbon neutral, becomes the most suitable option. Looking at Figure 6.3 it is evident that rock has a significantly lower carbon footprint compared to MagnaDense Concrete, which has the highest carbon footprint. Regular concrete and geopolymer concrete fall in between, with moderate carbon footprints in comparison with Rock. When the requirement for a 50-year lifespan is not that strict anymore, carbon-neutral and carbon-negative materials become viable options. However, low-carbon materials are suitable only for wave heights under 3 meters. Bamboo and jute require more maintenance due to their shorter lifespans. Incorporating fascine mattresses from brushwood which can sequestrate carbon, can help offset emissions from rock and sediment blocks. Key challenges include maintaining structural integrity, managing increased maintenance needs, ensuring material durability to optimize these materials for carbon-neutral construction.

Sub-question 4: How can the integration of sustainable materials and innovative design approaches contribute to the development of a carbon-neutral breakwater?
Integrating sustainable materials and innovative design approaches can significantly reduce the carbon footprint of breakwater projects. This includes employing life-cycle assessment (LCA) criteria to enhance energy efficiency and plan for end-of-life stages. Evaluating various design alternatives ensures that the most sustainable options are chosen. Additionally, using locally available materials minimizes transportation emissions, further supporting carbon neutrality efforts in breakwater construction. Moreover, this approach encourages further research into new materials and their optimization. By refining these materials, researchers can enhance their durability and sustainability, making them more suitable for carbon-neutral breakwater projects. This ongoing development is crucial for achieving fully carbon-neutrality in breakwater construction.

Final Conclusion
In conclusion, achieving carbon neutrality in breakwater construction demands a comprehensive approach that integrates accurate carbon quantification tools, alternative transportation methods, sustainable materials, and innovative design concepts. The research indicates that while integrating sustainable materials and innovative designs can significantly reduce carbon emissions, challenges related to long-term durability, structural integrity, and environmental impact must be addressed. By continuously enhancing assessment tools, adopting eco-friendly transportation technologies, optimizing material selection, and rigorously testing new designs, the construction industry can progress toward carbon-neutral breakwaters. This integrated approach provides a robust breakwater design while promoting environmental responsibility, paving the way for future innovations in sustainable breakwater constructions. Moreover, it offers valuable insights in different situations, highlighting that even in a mild environment like the Braassemermeer, concessions are necessary to achieve carbon neutrality. In cases of mild loads requiring relatively small armour layers, the core structure becomes dominant, emphasizing the use of sustainable materials, such as recycled materials as core. This approach shows promise as an effective option for reducing the carbon footprint in the construction of carbon neutral breakwaters.

9 Recommendations

Long-term performance of low-carbon materials (e.g. bamboo and brushwood)

- Conduct extensive field testing and long-term monitoring to validate the durability and effectiveness of low-carbon materials by installing test sections of breakwaters in diverse marine environments and observing their performance over several years for wear, degradation, and maintenance needs.

Impact of alternative fuels on overall sustainability:

- Conduct life-cycle assessments (LCA) to understand the full environmental impact of these alternative fuels compared to conventional fuels.
- Develop infrastructure to support the adoption of alternative fuels in construction projects, including refueling and maintenance facilities.

Improvement and standardization of LCA tools for accurate environmental impact assessments:

- Further developing the tools so that they become an independent and accurate reliable measure to compare design and execution methods.
- Update LCA tools regularly to include the latest data and methodologies, ensuring accurate and comprehensive environmental impact assessments.
- Standardize LCA tools across the industry to facilitate consistent and comparable results.
- Incorporate local and regional data to improve the relevance and accuracy of LCA results for specific project locations.

Include indirect emissions (transport equipment to location):

- Factor in the carbon emissions associated with transporting construction equipment to the project site in environmental impact assessments.
- Incorporate these indirect emissions into the overall carbon footprint calculations to provide a more accurate assessment of the project's environmental impact.

Exhaustibility of resources:

- Investigate the availability and sustainability of resources used in breakwater construction to ensure they are not being depleted faster than they can be replenished.
- Promote the use of renewable and abundant materials to reduce dependence on exhaustible resources.
- Develop and implement resource management plans that prioritize conservation and sustainable use of materials.

Sourcing of raw materials:

- Sustainable Extraction Techniques: Developing and optimizing methods that minimize environmental impact and improve energy efficiency in material extraction.
- Renewable Energy Integration: Investigating the use of renewable energy sources in the extraction and processing phases.

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A

Material Specifications

This appendix provides additional material specifications on materials presented in Chapter 4.

A.1. Concrete

Table A.1: Concrete mixtures with densities and corresponding carbon emissions using Ordinary Portland Cement (OPC) and blast furnace slag (Miller et al., 2015)

Mixture Density (kg/m^3)	**w/b** (kg/kg)	Cement (kg/m^3)	Fly ash (kg/m^3)	Water (kg/m^3)	Fine aggr. (kg/m^3)	Coarse aggr. (kg/m^3)	Carbon FP ($kgCO2/m^3$)	Strength Class
2262	0.33	180	360	180	490	1052	210	C25/30
2274	0.29	252	360	180	465	1017	290	C35/45
2295	0.33	246	282	176	509	1082	280	C25/30
2302	0.38	252	216	180	544	1110	280	C30/37
2307	0.29	317	282	176	484	1048	350	C40/50
2316	0.45	252	144	180	593	1147	270	C25/30
2320	0.33	317	211	176	520	1096	340	C50/60
2326	0.56	246	70	176	660	1174	260	C30/37
2328	0.38	324	144	180	558	1122	340	C35/45
2342	0.45	324	72	180	611	1155	340	C40/50
2347	0.45	425	0	193	607	1122	430	C40/50
2346	0.33	387	141	176	534	1108	400	C40/50
2355	0.38	396	72	180	572	1135	410	C40/50
2363	0.56	351	0	195	670	1147	360	C30/37
2363	0.38	507	0	195	565	1096	510	C50/60

Table A.2: High-density Concrete mixtures with corresponding carbon emissions (cradle-to-gate) using Ordinary Portland Cement (OPC) and MagnaDense (MD) (Exterra b.v., 2006)

Mixture Density (kg/m^3)	**w/b** (kg/kg)	**Cement** (kg/m^3)	**Water** (kg/m^3)	**Fine** aggr. (kg/m^3)	**Coarse** aggr. (kg/m^3)	**MD08/20** (kg/m^3)	**Additives** (kg/m^3)	**Carbon FP** (kg/m^3)	**Strength Class**
2900	0.55	330	180	721	410	1195	64	311	C40/50
3100	0.54	330	178	721	180	1628	64	311	C40/50
3300	0.54	330	177	671	0	2058	64	311	C40/50
3500	0.68	360	243	169	0	2661	68	338	C35/45
3500	0.53	359	191	367	0	2545	39	338	C40/50
3700	0.53	382	204	84	0	3031	0	360	C40/50
3900	0.53	350	186	0	0	3358	1318	332	C40/50

A.2. Geotextile Tubes

Technical properties

The behaviour as mass-gravity units requires the assessment of possible failure modes. A distinction can be made between external and internal failure modes. The external failure modes address the failure of the total structure, while the internal failure modes address the failure of an individual geotextile tube. In the design, safety factors are applied to cope with these limit states. There are 6 external failure modes that are described here. In figure A.1, you can see a schematisation of the various failure modes.

Both sliding and overturning stability are important limit states, especially for geotextile tubes with a diameter of D<2 m (Lawson, 2008). In the case of very large geotextile tubes and soft soil, bearing capacity becomes more important. Global stability is crucial when multiple geotextile tubes are required. Scour of foundations can happen during the complete lifetime of the structure, but if it does it can cause failure in the form overturning. When the foundation is sensitive for scouring, a scouring apron can be placed. If the foundation of the geotextile tubes is compressible, foundation settlement can take place due to the weight. In the case of breakwaters, a certain height is required and thus is an assessment of the effect of foundation settlement needful. For a detailed research on the stability of geotextile tubes in varying configurations, one can read the study conducted by Deltares (Steeg and Vastenburg, 2010). For simplicity the stability of a geotextile tube can also be determined based on the approach of Pilarczyk (Albers et al., 2013):

$$\frac{H_s}{\triangle b} < 1 \qquad \frac{H_s}{\triangle d} < 1 \tag{A.1}$$

with b the width of the tube and d the mean height of the tube.

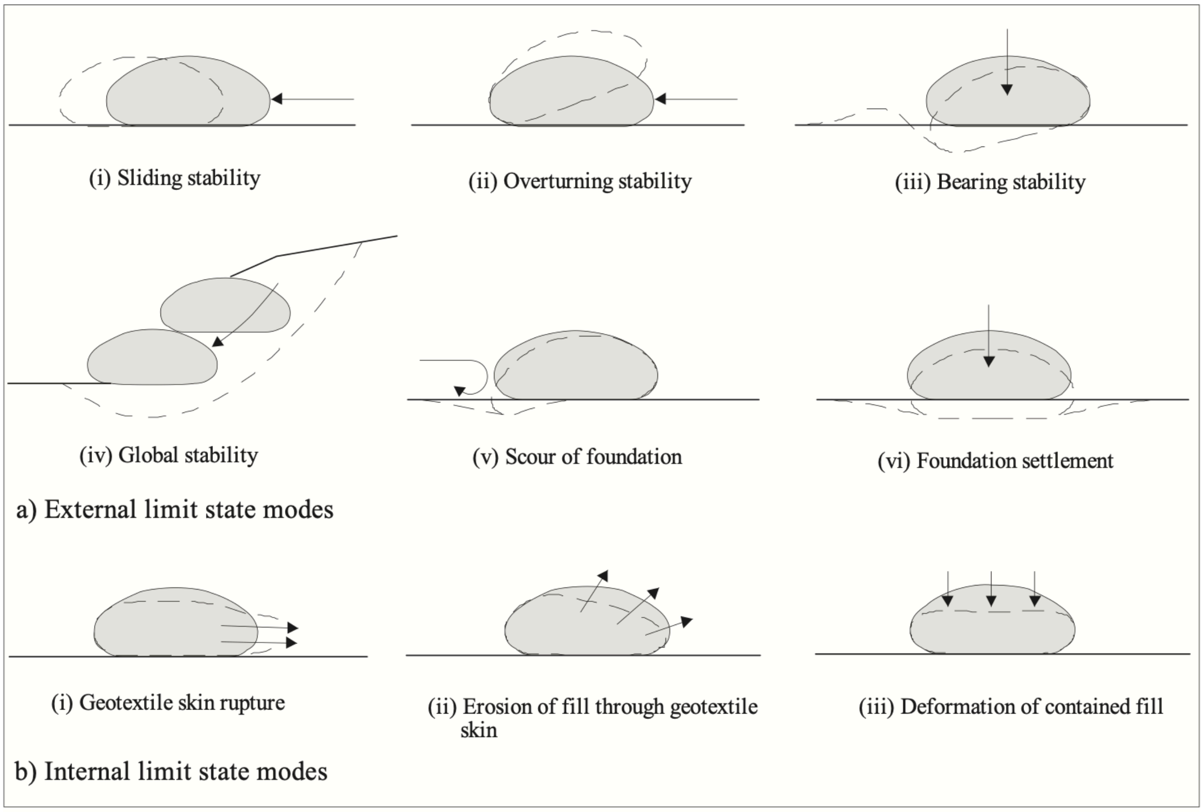


Figure A.1: Failure modes for geotextile tubes (Lawson, 2008)

B Interviews

This appendix provides the completely written out versions of the interviews with experts, which include information used in Chapter 4.

B.1. Interview 1

Person: Felix Leenders
Company: Van Hattum en Blankevoort
Language: English

B.2. Interview 2

Person: Edwin Zengerink
Company: Solmax/TenCate Geosynthetics Netherlands B.V.
Language: English

B.3. Interview 3

Person: Mr. Ivan ZH
Company: Boatup Geosynthetics
Language: English

B.4. Interview 4

Person: Wouter Guijt
Company: Nexus Energy B.V.
Language: Dutch

B.5. Interview 5

Person: Martin Rijnen
Company: LKAB
Language: English

Felix Leenders
Van Hattum en Blankevoort

I've heard a lot about your work with geopolymer concrete. Could you start by telling us a bit about your background and how you became involved with this material?

Felix Leenders: Absolutely. I've been in the field for nearly 10 years, having graduated from TU Delft in 2014. Initially, I started as a constructor but soon realized many in my field weren't deeply knowledgeable about concrete. This led me to specialize as a materials consultant, focusing on concrete technology, which I found incredibly engaging. My journey with geopolymer concrete began about five or six years ago and has since been a significant part of my work.

The most pressing question I have is regarding the feasibility of using geopolymer concrete for a breakwater. What are the potential challenges and advantages? I believe it could be a viable option. Could you elaborate on this point?

Felix Leenders: Certainly. The primary consideration for any material used in a breakwater is its mechanical strength, specifically its compressive strength. That's the starting point. But before we dive deeper into that, I'm curious about your level of familiarity with geopolymer concrete. How much do you know about it?

Given the focus on sustainability and reducing carbon emissions, how do you see geopolymer concrete fitting into the future of construction, especially for projects like carbon-neutral breakwaters?

Felix Leenders: Geopolymer concrete is an excellent material for such applications. Its manufacturing process significantly reduces CO2 emissions compared to traditional concrete, making it a valuable asset for sustainable construction. Moreover, its mechanical properties and durability in harsh conditions, like those encountered in marine environments, make it an ideal choice for projects like breakwaters.

Could you delve a bit deeper into the differences between traditional and geopolymer concrete, especially concerning their composition and environmental impact?

Felix Leenders: Given your background in hydraulic engineering, let's start with the basics. I'll share my screen to make this easier. I recently presented on geopolymer concrete, which should provide a good basis for our discussion. Both traditional and geopolymer concrete contain coarse aggregates, like gravel, sand, and water. The fundamental difference is that traditional concrete uses cement as a binder, while geopolymer concrete does not.
In traditional concrete, the binding of aggregates is achieved through a chemical reaction between cement and water, forming what's known as cement paste or cement stone. Cement itself comprises various components, predominantly Portland clinker in the case of CEM I. However, in infrastructural applications like breakwaters, we often use cements with a high content of industrial by-products, such as slag, in CEM III types, significantly reducing the cement content.

Geopolymer concrete, on the other hand, replaces cement with a combination of a precursor and an activator, creating the geopolymer paste. This precursor is typically a mix of industrial by-products like slag and fly ash, both of which are also found in some types of conventional cement but without the Portland clinker. This substitution is what fundamentally distinguishes geopolymer from traditional concrete, though in practical terms, the product shares many characteristics with its conventional counterpart, including appearance and workability.
Thus, when assessing geopolymer concrete's feasibility for breakwaters, we consider its mechanical properties, such as compressive strength, alongside its environmental advantages, like reduced carbon footprint due to the absence of Portland cement.

Could you elaborate on the relationship between compressive strength, tensile strength, and modulus of elasticity in both traditional and geopolymer concrete, and how these properties influence the suitability of geopolymer concrete for breakwaters?

Felix Leenders: Certainly. When we talk about concrete's suitability for applications like breakwaters, we're primarily concerned with its mechanical properties. Let's take compressive strength, for instance. If you have a C30/37 concrete, it means the concrete has a specific compressive strength, which is accompanied by a certain tensile strength (fctm) and a formula that correlates it with the compressive strength.
For a C30/37, the modulus of elasticity is around 33 GPa, and this value is determined by a formula that's derived from the compressive strength. Essentially, if you know the compressive strength, you can determine the corresponding tensile strength and modulus of elasticity, which are all in a certain ratio to one another. This relationship isn't an exact science but provides a range within which these properties vary. For example, the specified tensile strength for a C30/37 might be 2.9 MPa, but it could be as low as 2.7 or as high as 3.0 MPa.

In geopolymer concrete, these relationships hold similarly, meaning the material behaves in ways familiar to those versed in traditional concrete's behavior. However, geopolymer concrete typically has a slightly higher tensile strength (about 0.5 to 1 MPa more) and a 20 to 30 percent lower modulus of elasticity. This flexibility means that if compressive strength is a critical factor for your breakwater, geopolymer concrete can be engineered to meet specific strength requirements, whether that's 30 MPa, 35 MPa, or even higher.
Moreover, in terms of processing and application, geopolymer concrete is quite versatile. It can be poured, transported, and compacted much like traditional concrete. Although self-compacting mixes are not yet widely available, it's entirely feasible to create them. This adaptability has been demonstrated in various projects, including infrastructure components like pillars for the Port Authority of Rotterdam and other projects for Rijkswaterstaat, underscoring geopolymer concrete's practical viability for large-scale, structurally demanding applications like breakwaters.

Moving beyond the mechanical properties, could you discuss the environmental durability aspects of geopolymer concrete, particularly in relation to its technical lifespan and suitability for marine structures like breakwaters?

Felix Leenders: Of course. When we consider materials for marine applications, their ability to withstand environmental conditions is crucial. This isn't just about mechanical strength; the technical lifespan, especially in aggressive environments like sea water, becomes a pivotal factor.

Let me focus on environmental durability classes for a moment. The geopolymer concrete we utilize is robust across all severe environmental classes, including XA3 (high sulfate exposure) and XS3 (high chloride exposure from seawater), making it highly suitable for marine applications.

Considering breakwaters, which are exposed to sea conditions, the interaction with chlorides and sulfates is inevitable. Traditional concrete, particularly those based on Portland cement, can be vulnerable to sulfate attack, leading to significant swelling and degradation. This is primarily due to the presence of tricalcium aluminate (C3A) in Portland cement, which reacts adversely with sulfates.

Geopolymer concrete, in contrast, does not contain Portland cement or C3A, thus offering a significantly reduced susceptibility to sulfate attack. This inherent resistance makes geopolymer concrete an excellent choice for breakwaters, providing enhanced durability against the sulfate-rich environment found in seawater.

Additionally, while chloride penetration is a concern for the corrosion of reinforcement in conventional concrete structures, it's less of an issue for geopolymer concrete, especially in applications like unarmoured breakwaters where corrosion of reinforcement doesn't apply.

In summary, the technical lifespan and environmental durability of geopolymer concrete, coupled with its mechanical properties, make it an exceptionally suitable material for constructing breakwaters in marine environments.

That's impressive. However, given the innovative nature of geopolymer concrete, can you talk about the status of certification and standardization for this material? How does this impact its adoption in the construction industry, especially for critical infrastructure like breakwaters?

Felix Leenders: Currently, geopolymer concrete lacks formal certification, primarily because there aren't established standards specific to this material yet. This absence of certification is a significant hurdle since certification acts as a form of validation that a material meets certain standards. For prefabricated elements, the situation might be slightly different because standards can be applied to the finished product, which could then be certified to demonstrate compliance with those standards.

In the concrete industry, particularly for projects where the concrete arrives as a semi-finished product at the construction site, the lack of standards for geopolymer concrete means there's no certification for the material itself. The regulatory framework, including the Eurocodes which provide the technical standards for building and civil engineering works, doesn't currently accommodate geopolymer concrete because, by the strict definition, "concrete" is a material that includes cement, aggregate, and water. Since geopolymer concrete does not contain cement — at least not in the traditional sense — it technically doesn't qualify as "concrete" under these definitions.

Therefore, we often refer to it using the more accurate term "Alkali Activated Cementitious Material" (AACM) to reflect its nature and composition accurately. Despite these nomenclature and certification challenges, we approach the practical application of geopolymer concrete from a standpoint of equivalence. By demonstrating that geopolymer concrete meets or exceeds the performance characteristics of traditional concrete, including safety, durability, and environmental impact, we can argue for its use based on the principle of equivalent performance.

To navigate the regulatory landscape, we compile comprehensive dossiers detailing geopolymer concrete's properties, comparing them directly to those of traditional concrete to establish this equivalence. This dossier is then submitted for approval on a project-by-project basis, a process that, while somewhat cumbersome, allows for the use of geopolymer concrete in specific applications, including for structures like breakwaters, where its environmental and mechanical advantages are particularly compelling.

Regarding the environmental impact of geopolymer concrete, you mentioned significant CO2 savings compared to traditional concrete. Can you elaborate on these savings and the relationship between concrete strength and CO2 emissions?

Felix Leenders: The geopolymer concrete mixture we use achieves a CO2 reduction of 50% compared to a CEM 3b mixture, and even more impressively, about 80% when compared to CEM 1. This substantial reduction is largely due to the elimination of clinker, which is the most carbon-intensive component of traditional cement.

So, is there a direct correlation between the strength of the concrete and its CO2 emissions?

Felix Leenders: Indeed, there is a relationship, though it's not straightforward. The formula for predicting the strength of concrete involves several factors, including the cement's norm strength and the water-cement ratio. The key here is that reducing the water-cement ratio, which is essential for achieving higher strength classes, generally requires increasing the cement content. Since cement production is the primary source of CO2 emissions in concrete manufacturing, a higher cement content directly leads to higher emissions.

And how does this apply to geopolymer concrete?

Felix Leenders: With geopolymer concrete, while we eliminate the use of traditional cement, achieving higher strengths still necessitates increasing the quantity of the binder, which in this case involves materials like fly ash and slag, activated by chemical solutions. These materials do have associated CO2 emissions, albeit significantly lower than those of Portland cement. Therefore, while the correlation between strength and CO2 emissions still exists for geopolymer concrete, the overall environmental impact remains substantially lower than traditional concrete options. Yet, regulations are evolving regarding materials like fly ash and slag.

Does this mean the CO2 savings could change with evolving regulations or advancements in geopolymer concrete technology?

Felix Leenders: Precisely. The regulatory landscape and how emissions from industrial by-products like slag are accounted for are changing. These changes could affect the calculated CO2 savings of geopolymer concrete. Nonetheless, the fundamental principle that geopolymer concrete uses industrial by-products, which would otherwise contribute to waste, ensures its place as a more sustainable option in the construction industry.

On a different note, considering the potential for recycling geopolymer concrete, is it feasible to repurpose this material after a structure's life cycle ends?

Felix Leenders: Yes, research, including studies by SGS-Intron, indicates that geopolymer concrete is 100% recyclable. This means that, just like traditional concrete, geopolymer concrete can be crushed and reused as aggregate in new concrete mixes, closing the loop on its life cycle and reinforcing its sustainability credentials. This capacity for recycling further strengthens the case for geopolymer concrete as an environmentally friendly material for the future of construction.

Edwin Zengerink
Solmax / TenCate Geosynthetics Netherlands B.V.

When considering the design and location for a breakwater, how do you approach the analysis of the CO2 emissions?

Edwin Zengerink: Well, when it comes to CO2 emissions, it's essential to understand the material sources—whether stone or sand—and their transport distances. We utilize a CO2 calculator that can significantly highlight the difference in emissions between traditional rock breakwaters and those using geotubes. This tool allows us to demonstrate potential CO2 savings based on the construction's principal section.

Interesting. And how does the origin of materials like stones affect the CO2 emissions in breakwater construction?

Edwin Zengerink: Stones for breakwaters in the Netherlands often come from Norway or Belgium, affecting the CO2 emissions due to transport. Using geotubes can provide a sustainable alternative, potentially saving a significant amount of CO2, especially when compared to traditional rock breakwaters.

Can you elaborate on the necessity of covering geotubes with stone material?

Edwin Zengerink: Covering geotubes with stone is generally advisable to protect against UV damage and mechanical impacts. Even though geotubes are designed to be UV stable, external factors like vibration and mechanical damage can still pose risks. Stone covering acts as a protective layer, enhancing the durability of the underlying geotubes.

Have there been applications of geotubes for submerged breakwaters?

Edwin Zengerink: Yes, we've implemented submerged breakwaters without stone cover in places like off the coast of France. These structures can effectively break large waves without the need for stone covering, thanks to their placement at specific depths where direct sunlight and mechanical damage are less of a concern.

Moving on to the durability of geotextile tubes in different water types, is there a difference in their lifespan between saltwater and freshwater environments?

Edwin Zengerink: The material used in geotextile tubes, polypropylene (PP), is highly durable in both saltwater and freshwater. Our tests on thermo-oxidative resistance indicate a lifespan of over 100 years when the tubes are buried and protected from direct exposure, with no significant difference between salt and freshwater environments.

Can you explain the importance of certification for your products?

Edwin Zengerink: Certainly. All the products we use, especially in construction projects like breakwaters, must be CE-certified. This certification ensures that our products meet EU safety, health, and environmental protection standards. Within the CE certification, there's a document known as the Declaration of Performance (DOP), which details the performance characteristics and expected lifespan of the product. This document is crucial not only for compliance but also for providing consultants and engineers with the necessary information to guarantee the expected performance and durability of the structure they're designing. We make sure that all these details are clearly outlined in the DOP, which I can send to you for any product we use in our breakwater projects. It's also detailed in the information we provide, ensuring transparency and reliability in what we offer.

How do you calculate the CO2 emissions associated with constructing breakwaters using geotextile tubes?

Edwin Zengerink: Yes, we utilize a comprehensive model that integrates global standards from the EcoInvent database to assess the CO2 footprint of constructing breakwaters locally. This model accounts for all aspects of construction, including the energy required to fill the geotextile tubes and to transport and lay down stones from quarries to the site. Currently, our calculations are based on diesel usage, which is the norm, but we're seeing a trend towards more electrically powered equipment. This shift isn't yet reflected in our model, but it's an important consideration as we aim to reduce our environmental impact further.

Transport is a major contributor to CO2 emissions, especially for materials sourced from distant locations, like the 30,000 tons of stone we might bring in from Norway. This aspect of the project often outweighs the emissions from on-site operations, even with the shift towards more sustainable practices like using electric equipment. It's a critical area we're continuously working on to improve our overall sustainability.

What considerations are there regarding the filling material for geotextile tubes?

Edwin Zengerink: We recommend using sand due to its ease of flow into the tubes and compatibility with hydraulic filling methods. Larger materials like stones are not suitable for suspension and filling, as they can settle quickly and complicate the filling process.

Lastly, is there potential for microplastic release from geotextile tubes, and are there any examples of long-term applications of these tubes?

Edwin Zengerink: While the risk of microplastic release is minimal, some abrasion during the filling process might occur. However, projects like the one off the coast of Sete in France, where tubes have been in place for over a decade, demonstrate the durability and minimal environmental impact of geotextile tubes over the long term.

Mr. Ivan ZH
Boatup Geosynthetics

What is the carbon emission related to the production of geotextile tubes?

Ivan: The carbon emissions associated with geotextile tube production are impacted by the material choice and manufacturing process. The exact figures vary based on sourcing and production methods.

Are there any innovations or practices in the manufacturing process that aim to reduce the carbon footprint of geotextile tube production?

Ivan: Yes, innovations and practices are being developed to reduce the carbon footprint. By improving efficiency, minimizing waste, and considering material sourcing, we can reduce emissions.

How does the transport of geotextile tubes to construction sites impact their overall carbon emissions?

Ivan: Transportation to construction sites can significantly impact emissions due to the weight and bulk of the tubes. Optimizing logistics and choosing local suppliers can help mitigate these effects.

How do environmental factors like UV exposure, salinity, and temperature variations affect the lifespan of geotextile tubes in marine settings?

Ivan: The most important factor affecting the lifespan of geotextile tubes is UV exposure. For instance, geotextile tubes will lose 50-60% of tensile strength in less than 5 years with UV exposure, and the expected lifespan is about 10 years in this situation. When not exposed to UV, a lifespan of 20-30 years is achievable. Salinity doesn't significantly affect the pH value and thus has little effect on tube lifespan. Similarly, temperatures below 70°C don't greatly impact durability.

Are there significant differences in the durability of geotextile tubes used in freshwater versus saltwater environments?

Ivan: The pH value affects the durability of geotextile tubes. However, salinity isn't a major factor influencing pH, so there isn't a significant difference between freshwater and saltwater.

Can you share any case studies or research findings on the long-term performance of geotextile tubes in coastal protection projects?

Ivan: Unfortunately, we don't have this type of case study yet.

Are there any risks of the release of microplastics from the degradation of geotextile tubes? If so, are there biodegradable or eco-friendly alternatives to traditional geotextile materials that reduce the risk of microplastic pollution?

Ivan: The relationship between degradation factors and microplastic formation is still unclear due to a lack of studies globally. We use polypropylene to manufacture geotextile tubes, which isn't biodegradable but is degradable. Polypropylene degrades in around 20-30 years compared to 500 years for polyethylene and polystyrene. Thus, geotextile tubes are considered eco-friendly.

What specific characteristics are required of the infill material for geotextile tubes to ensure effectiveness and durability in breakwater applications?

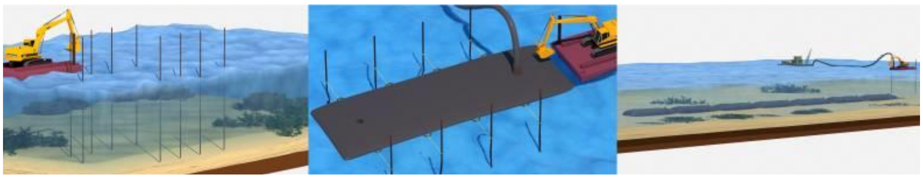
Ivan: The filling material is dredged from the seabed. If the material can pass through the pump feeding system, it's suitable for use. The specific gravity should ideally be no more than 2.7.

How does the choice of infill material affect the environmental impact of using geotextile tubes in coastal engineering projects?

Ivan: Infill materials like clay, silt, and sand have no significant environmental impact difference between them.

Are there guidelines or standards for selecting and sourcing infill materials to balance construction efficiency and environmental sustainability?

Ivan: No, the primary rule is to use materials that can be sourced from the site. Here is how they are filled.



How are geotextile tubes designed to accommodate the dynamic forces and conditions typical of coastal and underwater environments?

Ivan:
- Choose the right raw materials and add additives to combat environmental chemicals.
- Produce high-tenacity yarn to ensure the tubes are strong.
- Special weaving designs offer strong mechanical and hydro performance.

Can geotextile tubes be recycled or repurposed at the end of their service life to minimize waste and environmental impact?

Ivan: No, they can't be.

Are there any ongoing research or development efforts aimed at improving the sustainability and performance of geotextile tubes in coastal protection?

Ivan: We're working on using recycled polypropylene to produce geotextile tubes, aiming to save energy.

Wouter Guijt
Nexus Energy BV

Kan je iets vertellen over het type apparatuur dat gebruikt wordt en hoe jullie energieoplossingen hierin passen?

Wouter Guijt: Ik laat even een plaatje zien. Op dit plaatje is denk ik wel een beetje het type apparatuur te zien dat jullie zullen gebruiken bij de aanleg van dat soort projecten. Dit zijn dan allemaal elektrische graafmachines, elektrische dumptrucks, elektrische kranen, etc. Wat wij eigenlijk doen met deze waterstofcontainer, die leveren wij niet zelf, maar er zijn een hoop mensen die dat kunnen leveren. Wij leveren een blauwe doos. Daar zitten dan nu 250 ampère aansluitingen aan, en wij kunnen daarmee 200 kilowatt opwekken. In deze witte container zit netto na conversie, door onze brandstofcel, iets meer dan 7 megawattuur aan energie.

Als je dat zou vergelijken met batterijcontainers, dan heb je 20 tot 30 containers van deze afmetingen nodig. Dus dat is gewoon interessant. En dan kun je deze units van ons gewoon neerzetten om die apparatuur op te laden. De graafmachines en kranen hebben allemaal wel een accu in zich, waarmee ze meestal net wel of net niet een dag kunnen werken. Zodra ze dan even stilstaan, staat onze generator weer stand-by om helemaal emissieloos stroom te leveren.

Op dit moment leveren we 200 kilowatt, en we kunnen continu 120 kilowatt leveren. Eind dit jaar, begin volgend jaar, kunnen we continu 250 kilowatt leveren, en pieken van 400 kilowatt een uur lang. Die capaciteit blijft steeds verder toenemen. Dan kunnen we dus ook snelladers toepassen, zoals DC-snelladers, dat soort dingen. Praktisch gezien zal je de komende 2-3 jaar nog steeds kleine batterijcontainers hebben op zo'n bouwplaats. Voor de graafmachines hebben ze bijvoorbeeld een 10 foot container met 400 kilowattuur capaciteit en een snellader, zodat je snel kunt laden.

In de tijd dat de machines aan het werk zijn, kunnen wij natuurlijk met behoorlijk wat vermogen die batterijen weer opladen. Je kunt dus ook meerdere van dat soort kleine boosterstations op een bouwplaats neerzetten. Op een groot bouwterrein, zoals waar je net over had, zet je gewoon 1 of 2 van die units van ons neer, die continu emissieloos werken. Dus ik denk dat dit een praktische manier is om dit soort apparatuur op locatie te gebruiken.

Want hoelang duurt het om op te laden? Een normale oplader en een snelle oplader?

Wouter Guijt: Ja, dat durf ik echt niet te zeggen, want het hangt een beetje van die laders af. Wat we nu kunnen is volgens mij met 175 kilowatt snel laden. Laten daar nou meestal 300-400 kilowattuur batterijen in zo'n graafmachine zitten. Dus met een paar uurtjes zou je zo'n graafmachine wel vol hebben. Maar wat ze meestal gewoon doen is dat ze zorgen dat de graafmachine ‘s nachts opgeladen is. Dan gaan ze er ‘s ochtends mee werken en in de middag hangen ze hem er even aan. ‘S nachts moet je dus gewoon laden, maar overdag kunnen wij dus weer die boosterstations opladen. Wij doen dat dan met 120 kilowatt continu per blauwe doos van ons. Dat wordt dan 250 kilowatt volgend jaar.

Hoe werkt dat dan, dat opladen van zo'n powerstation? Wordt dat gewoon aan het lokale net opgeladen?

Wouter Guijt: Nee, dat doen wij dus. Dus je hebt eigenlijk qua afmetingen nog een keer zo'n blauwe doos staan als die wij hebben. Alleen die zit dan helemaal vol met batterijen, dat is dan 400 kilowattuur. Die hangt met een snellader aan die graafmachine en die laadt in twee uur die graafmachine vol. Alleen wat wij doen is gewoon continu met 120 kilowatt allemaal van dat soort boosterstations opladen. Dus je hebt het net niet meer nodig.
Je hebt geen bouwaansluiting nodig, je hebt geen zware stroomaansluiting nodig. Je kan alles uit die waterstofcontainer halen. En wij zetten die waterstof om naar stroom.
Dat die stroom nou meteen in een graafmachine stopt of dat je die in een accu stopt. Dat is aan de klant. Alleen ik denk dat bij dat soort grote projectlocaties waar je dan over praat bij een golfbreker, en dan heb je zomaar 10, 20, 30 elektrische stukken equipment rondrijden, is het volgens mij slimmer om op een paar strategische plekken die containers van ons neer te zetten. En dan op nog een paar meer plekken van die kleine booster stationnetjes.

Ja precies. Leveren jullie ook zelf het materiaal qua graafmachines? Of zijn jullie echt volledig gefocust op de accu's? En hoe werkt dat met waterstof? Want volgens mij heb ik ergens gelezen dat waterstof redelijk lastig is om op te slaan.

Wouter Guijt: Ja, wij zijn volledig gefocust op die blauwe containers. Het opslaan van waterstof valt wel mee. Die witte container die je zag, daar zit gewoon waterstof onder druk in. En dit is maar van 1 van de leveranciers, er zijn er veel meer. En dat houden ze onder 350 bar of 500 bar in zo'n container. Nou, er zit bij 350 bar zo'n 400 kilo waterstof in zo'n container. En die 400 kilo is netto na conversie, bij ons is dat dik 7 megawattuur aan energie. Dus het is wel lastig om op te slaan. Maar dat is niet het probleem met waterstof, het probleem is dat er heel veel energie in een volume-eenheid zit. Maar die volume-eenheid neemt gigantisch veel volume in. Of veel energie naar gewicht eenheid, dat is ook moeilijk te zeggen. Maar dat gewicht neemt heel veel volume in. Daardoor moet je het comprimeren, of vloeibaar maken, of er ammonia van maken. Maar dat is allemaal nog in kinderschoenen. En op basis van gasvormig waterstof, kunnen wij nu gewoon al stroom maken.

Wat is de vooruitblik over een aantal jaar? Wat zijn de innovaties?

Wouter Guijt: Dat de energiedichtheid van ons systeem, dus wij hebben nu 200 kilowatt in een halve 10-footer. Die energiedichtheid zal steeds verder omhooggaan. Dus ik denk dat wij eind volgend jaar wel misschien bijna een megawatt in een 10-footer kunnen stoppen. En dan aan de kant van de waterstofopslag, dat gaat onder steeds hogere druk. Dat zal gebonden gaan worden aan een drager, een vloeibaar, of aan natrium borohydride, dat soort dingen. Dan zal de energiedichtheid van waterstof omhooggaan. Dus dan zal je in die 20-footsscontainers, die nu 7 megawattuur mee kunnen nemen, dan misschien wel 14, 15 of 20 megawattuur mee kunnen nemen. Dat zal aan die kant ook weer verder gaan.

En zien jullie dan ook de meeste potentie in waterstof ten opzichte van andere duurzame brandstoffen?

Wouter Guijt: Ja, het is eigenlijk wat je ook ziet, daar hebben wij ons een beetje op gefocust. Of het nou Shell is of wie dan ook. Iedereen zegt het wordt waterstof.
Alleen in welke vorm, of dat dan ammonia wordt, dat is waterstof met stikstof. Of methanol, waterstof met CO2. Of vloeibare waterstof. Dat weet ik niet, dat zal ook wel anders worden. Net als dat je nu benzine, diesel en gasolie en zware stookolie voor de scheepvaart hebt. Dat zijn allemaal vormen van aardolie.
Maar iedere toepassing, en kerosine is ook hetzelfde natuurlijk. Iedere toepassing gaat zijn eigen energie dragen. En daar zal in de toekomst door de marktpartijen zoals Shell, op een gegeven moment een afslag in genomen worden. En daar kunnen wij gewoon op volgen. Ik denk dat benzine vervangen zal worden door accu's. Net als autootjes, die kunnen ook prima op accu's rijden. Maar diesel zal waterstof worden. Die kun je nu al goed onder druk tanken op meerdere plekken in Nederland. Vanuit de Europese Unie moet je in 2030, geloof ik, op iedere 150 kilometer een waterstoftankstation hebben. Dat zal gasvormige waterstof zijn. Dus vrachtwagen, dieselauto's, zullen allemaal op waterstof gaan rijden. Schepen, etc, geen idee. Ik denk ook dat die grote dumptrucks die je op de plaatjes zag, die zullen misschien wel zelf een waterstofgenerator in zich hebben zitten. Maar misschien ook niet. Misschien is het veel goedkoper en makkelijker om dat op accu's te doen. En dan op een lokale plek, op zo'n bouwplaats, zo'n waterstofgenerator in te zetten. Geen idee. Gaan we wel zien.

Wat is dan de CO2-uitstoot voor een dag opladen van die machines? Hebben jullie daar iets van documenten van?

Wouter Guijt: Nul. Helemaal nul. En stikstof ook nul.

Dus jullie LCA is in principe gewoon helemaal nul?

Wouter Guijt: Ja, het is helemaal nul. Geen stikstof, geen CO2, geen fijnstof, helemaal niks. Het enige wat er bij ons uitkomt is warm water. Dus wij filteren de lucht in feite ook nog eromheen.

En wat zijn op dit moment de grootste beperkingen om het overal in te zetten?

Wouter Guijt: Onbekend maakt onbemind. Dat is een beetje waar we nu tegenaan lopen. Er is net een nieuwe omgevingswet live gegaan sinds januari, waar ook het gebruik van waterstof in de bebouwde omgeving wat beter beschreven wordt. Dat was voor nu nog een beetje spannend. Dus deze hoeveelheden die wij gebruiken, die kun je prima gewoon op een bouwlocatie neerzetten. Dat mag ook. Als je heel veel meer zou willen neerzetten, dan is daar qua wetgeving nog een uitdaging. Maar verder staat ons niet zoveel in de weg.

En wat zijn de toepassingen als je machines op het water hebt? Of die op het water werken? Is daar nog een beperking in de mogelijkheden?

Wouter Guijt: Ik ga even een plaatje erbij zoeken. Dit is de machine zonder die koelunit erbovenop die je op het plaatje net zag. Dus zonder koeler kan die gewoon aan het koelwater koelen. En dan kun je hem zo neerzetten. Dit is een dieselelektrisch baggerscheepje. En daar kunnen we gewoon die dieselmotor vervangen door dit ding met een tank erachter op. Hier zie je ook een emissieloze bouwplaats. Hier zie je meteen het probleem als je, ook bij het soort projecten wat jij bedoelt, als je heel veel materiaal hebt en je het allemaal met accu's moet gaan doen, dan moet je heel veel accu's hebben, maar je moet vooral ergens een hele grote stroomaansluiting hebben.
Die heb je niet, dus je kan beter een paar van deze jongens neerzetten dan. Vliegtuigen kunnen we ermee aanvliegen, maar in een maritieme toepassing ga je dus gewoon de dieselmotoren uit het schip halen en die dozen van ons erin zetten. En daar hoeven wij qua hardware in de doos niks voor te wijzigen.
Onze omvormers kunnen ook gewoon elektromotoren aanzwengelen. Of die kunnen batterijen maken, maar dat maakt voor ons ding niet uit. We moeten in de software alleen een ander bitje aan zetten. Dat zie je hier waar we ook op het water een elektrische kraan opladen.

Merken jullie dat er al veel vraag naar is? Of zijn de hoeveelheden machines die al beschikbaar zijn op waterstof, is dat nog beperkt?

Wouter Guijt: Nee, er is heel veel vraag naar. Dat plaatje wat je net zag is ook een elektrische kraan met een accu erin, en wij laden dan die accu op. Dus het probleem wat je dus heel veel ziet waar mensen tegenaan lopen is dat we wel emissieloos kunnen bouwen met machines of accu's. Maar dat er geen zware netaansluiting is.
En daar zijn wij vooral een oplossing voor. Dat we die zware netaansluiting niet nodig hebben. Dus je kan alle andere batterijen gewoon met ons opladen.
En dat vinden mensen nog spannend en nieuw. En waterstof is allemaal onbekend. Er gaat een mythe rond dat dat allemaal hartstikke duur zou zijn.
Wij kunnen nu gewoon al goedkoper dan diesel, batterijen opladen met de huidige waterstofprijs. Mensen moeten het nog gaan leren kennen. Dat is het een beetje, denk ik.

Staat er ergens online een voorbeeld van waar jullie dit al toepassen. Misschien een document waarin uitgelegd staat hoe de uitstoot op nul blijft. En de prijs bijvoorbeeld.

Wouter Guijt: Op onze website zie je een filmpje van dat project wat ik net liet zien. Ja, er staat wel het en ander op de website, ja. We zijn maar inmiddels met z'n drieën.
Maar we waren altijd met z'n tweeën. Dus we hebben even de focus gehad op dat ding bouwen. En nu gewoon heel veel meters buiten de poort maken.
Als ik ineens 100 klanten zou hebben, zou ik ook een probleem hebben.

Want hoeveel zou je nu kunnen leveren?

Wouter Guijt: Nee, wij kunnen nu op jaarbasis ongeveer tussen de 10 en de 20 machines leveren. En dat wordt per jaar verdubbeld, eigenlijk.

Het verschilt natuurlijk per apparaat dat je gebruikt. Maar per box, hoeveel zou je dan kunnen opladen? Hoeveel machines?

Wouter Guijt: Oh ja, dat is een goeie vraag. Wij kunnen dus per box continu 24 uur per dag 120 kilowatt leveren. Dus 120 keer 24 aan kilowattuur kunnen we leveren. 3 megawattuur eigenlijk per dag.

En jullie zijn nu vooral gefocust op locatiematerialen. Gaan jullie ook kijken naar langere transportmogelijkheden? Of is dat een later stadium? Of misschien niet eens een doel?

Wouter Guijt: Die unit is ontworpen voor maritieme toepassingen. Dus hij is viervoudig redundant. En we zien dat daar nog heel veel regelgeving te doen is. Dus wij hebben de focus daarop. Maar we zien dat we hem ook als stand-alone op een bouwplaats kunnen gebruiken om batterijen, elektrische graafmachines, etc. op te laden.
Dus dat zijn een beetje de markten waar we eerst naar kijken. In en op het water. Ja, precies. Want in de binnenstad kun je natuurlijk ook prima met een batterijcontainer rijden. Maar als je meer en meer aan het werk bent, is het misschien wel makkelijker om zeven megawatt in een twintig footer te gebruiken.

Want promoten jullie nu ook dat daardoor kleinere batterijen nodig zijn?

Wouter Guijt: Nee, want er zit al een klein batterijtje bij ons in. Dus dat promoten we nog niet echt. We zijn ook niet zo hard aan het promoten.

Ik hoorde dat jullie ook wel in contact waren met de gemeente Rijnland? Of was dat niet zo?

Wouter Guijt: Ja, klopt. De waterschappen inderdaad. Die willen ook emissieloze werken laten uitvoeren. En wij zijn eigenlijk een van de weinigen die dat mogelijk kunnen maken zonder dat je met batterijen hoeft te slepen. Dus die zijn daar zeker in geïnteresseerd. Dan heb je hem in de Natura 2000 gebieden of in gebieden waar geen stikstof uitgestoken mag worden, juist nodig. Dan kun je gewoon emissieloos werken tegen concurrerende tarieven. En dat is natuurlijk wel interessant.

Kan ik hier ook iets vinden over die tarieven?

Wouter Guijt: Nee, dat denk ik niet. Maar op de markt nu kun je ergens 10 euro per kilo waterstof krijgen. Dan zit 33 kWh in een kilo waterstof. En wij hebben een rendement van 55%. Dus wij halen netto zo'n 18 kWh uit een kilo waterstof. Dan zit je dus ongeveer ergens tussen de 40 en de 50 cent per kWh. En dan hoef je niet te slepen met batterijen en dat soort dingen. Dus dat zijn de handigste getallen voor nu, denk ik.
Dus voor nu, daar zit een andere berekening weer aan ten grondslag, als je meer dan 300 liter diesel per dag verbruikt, is het nu al goedkoper om op waterstof te gaan werken. Omdat een dieselmotor van zichzelf uit zo inefficiënt is. En die wordt zo inefficiënt gebruikt. Een dieselmotor, zegt iedereen natuurlijk altijd, dat hij een 35% rendement heeft. Dat klopt als jij in je ideale koppel toeren draait. Maar dat doet niemand, want dan maak je te veel

toeren en dan verbruik je te veel. En als die machinist pauze heeft, staat hij ook een half uur stationair te draaien. Dus aan het einde van de dag heeft een dieselmotor vaak maar 20% rendement. Nou, als ik zeg dat het enige emissieloze alternatief voor diesel HVO 100 is, een soort biodiesel, dan zeggen ze dat de uitstoot daarvan vrijwel nul is. Er zit 10 kWh in een liter diesel. Als ik 20% rendement heb, haal ik er maar 2 uit. 2 kWh uit een liter diesel, maar HVO kost 2 euro per liter. Dus dan heb ik een euro per kilowattuur. Nou, wij zitten daar dus dik onder. Dat is het sommetje wat wij steeds met onze klanten maken.
En wat nu aangetoond is dat wij dat rendement hebben en dat diesel echt heel slecht is qua rendement. Er zijn ook rapporten van het TNO van dat dat echt rond die 20% maar ligt. En dat is een beetje het sommetje wat steeds meer klanten nu gaan maken.
Diesel is wel overal beschikbaar, maar wordt steeds duurder. Moet je die CO2-rechten nog gaan betalen straks, dat is bij ons niet. Dus het is eigenlijk 1 euro per kilowattuur diesel HVO versus 40-50 cent per kilowattuur bij waterstof.

Hieronder nog het rekensommetje:

1 L diesel heeft 10kWh energie in zich. Een dieselmotor heeft op z'n ideale punt in z'n koppel-toeren-kromme zo'n 35% rendement maar op dat punt wordt bijna nooit gewerkt omdat de motor dan te veel verbruikt. Daarnaast draait een motor veel op stationaire toeren, wat bijzonder slecht is voor z'n verbruik. Al met al zijn er studies die het nettorendement van de functionaliteit van een dieselmotor (dus echt gebruikte energie, niet het mechanische proces van energieomzetting) rond de 20% zetten.

HVO (soort diesel waarop gedraaid moet worden in natuurgebieden etc.) zit tegenwoordig op zo'n €1,80 per liter. Met een rendement van 20% op 10kWh zit je dus op 2kWh netto uit een liter dus €0,90 per kWh. Bij rode diesel zonder accijns etc. zit je op €0,80/L en dus op €0,40 per kWh.

H2 zit tegenwoordig in redelijk kleine volumes op €10-€13/kg. Grote volumes gaan richting €8.
1kg H2 heeft 33kWh energie in zich en onze omzetting zit gemiddeld op 55%. Verliezen bij stationair oid zijn er niet want dat treedt niet op.

33kW x 0,55 = 18,15kWh per kg.
€13 / 18,15 = €0,70 per kWh
€8 / 18,15 = €0,44 per kWh

Dat klinkt inderdaad wel positief.

Wouter Guijt: Ja, zeker. En hoe moet het verwerken in jouw opdracht? Hoe moet ik dat zien? Jij bent een soort studie en business case aan het bouwen voor zo'n emissieloze bouwplaats.

Ja, ik kijk naar het gehele plaatje. Dus ik kijk ook naar materialen die gebruikt kunnen worden in een golfbreker. Ik kijk naar het transport. Maar de grootste uitstoot zit nu nog in het transport van de materialen. Maar op de bouwplaats, als je daar al vermindering kan brengen, op zo'n manier bijvoorbeeld, daar zou heel veel winst mee behaald kunnen worden. Dus op deze manier ga ik ook dit soort toepassingen erin verwerken.

Wouter Guijt: Nou, leuk. Heb je daar nog wat nodig van mij? Wat plaatjes of andere dingen of zo?

Ja, graag. Als je wat achtergrondinformatie of documenten kan opsturen waar wat aspecten in uitgelegd staan. Dat zou alleen maar kunnen helpen.

Wouter Guijt: Ik zal wat foto's sturen en onze algemene folder. Kijk er maar even naar en als je specifieke vragen hebt over bijvoorbeeld die omzetting en die euro per kilo, zet maar gewoon in de mail en dan reageer ik daar wel even op. Dat is even makkelijker, denk ik, dan een hele berg informatie jouw kant op. Dus kijk er even naar. Ik stuur je een hoop plaatjes en een folder. Kijk maar wat je vragen hebt, stuur me dan.

Oké, helemaal goed. Dan zal ik het doen. Bedankt voor je tijd.

Wouter Guijt: Ja, succes ermee. En hou mij maar even op de hoogte hoe het loopt.

Martin Rijnen
LKAB

Can you start by explaining what your company does in Sweden with the material you're mining?

Martin Rijnen: Sure, in Sweden, we mine large quantities of a specific material that is used in various applications, including the concrete industry. This material is certified and fully applicable for use in concrete. However, while we have expertise in this material, we are not the ones who manufacture the concrete.

Okay thank you, let's go through my questions. How does the production process for concrete differ with this material?

Martin Rijnen: The production process for concrete remains the same. At a concrete plant, you specify the recipe you need. For high-density concrete, the process is identical except that instead of sand and gravel, this material, MagnaDense is used. The producer determines the recipe and the quantities required.

What differences arise during the mixing process compared to traditional concrete?

Martin Rijnen: The material is heavy, so careful consideration is needed during mixing and pumping. There are no significant differences between handling normal concrete and high-density concrete in terms of mixing and pumping.

How does this high-density concrete impact CO2 emissions?

Martin Rijnen: This is a bit complex. Comparing one cubic meter of normal concrete to one cubic meter of high-density concrete isn't straightforward. High-density concrete generally has higher CO2 emissions because the material is transported from Sweden, making the transport emissions a significant factor. However, in applications requiring substantial mass, high-density concrete can reduce the overall volume needed, thus potentially lowering the total cement required and balancing out the CO2 emissions.

Could you provide a specific CO2 emission value for producing a cubic meter of concrete with your material?

Martin Rijnen: We have an Environmental Product Declaration (EPD) and other documents detailing this. I recommend reviewing these documents for comprehensive information on the CO2 emissions associated with our material.

I noticed mentions of MD8S and MD20S in your EPD. Can you explain what these are?

Martin Rijnen: These are product names for different grades of our material, MagnaDense 8S and MagnaDense 20S. The actual mineral is magnetite, but we market it under these names. These variations allow you to calculate the CO2 emissions based on the specific grade used.

Can you give an example of the highest density you can achieve with your concrete?

Martin Rijnen: We have two types of concrete: regular mass concrete and structural concrete. For structural concrete, we can achieve densities up to 4000 kg per cubic meter. The CO2 emissions will depend on the amount of magnetite used in the mix.

Do you have a standard mixture for high-density concrete?

Martin Rijnen: Yes, I can send you examples of our mix designs. These include different densities and the corresponding CO2 emissions, allowing you to compare various options.

How do different types of cement impact the CO2 emissions?

Martin Rijnen: The type of cement used significantly affects CO2 emissions. There are various alternative cements with lower CO2 emissions, but they may not always meet specific performance criteria, such as fast curing times. The traditional Portland cement, commonly used, has a higher CO2 footprint.

How does cement content influence long-term durability?

Martin Rijnen: The cement factor is crucial for durability, depending on the environment the concrete will be exposed to. Different cements provide different levels of resistance to elements like acids. You can find more detailed information in resources like the beton lexicon.

What are the implications of recycling and reusing concrete waste on CO2 emissions?

Martin Rijnen: Magnetite, being ferromagnetic, is easier to separate during recycling compared to normal aggregates. This makes recycling more efficient and potentially lowers the CO2 emissions associated with concrete waste management.

How do regulations and industry standards affect the development of new concrete technologies?

Martin Rijnen: Current regulations can be a hindrance, as they often lag behind technological advancements. For example, geopolymer concrete, which is more CO2-friendly, meets practical performance standards but doesn't always meet regulatory definitions. The industry needs incentives to adopt and reward sustainable practices.

Finally, how do different cement types and densities affect the performance characteristics of concrete?

Martin Rijnen: Performance characteristics, like strength, are influenced by the type of cement and the density of the concrete. High-strength concrete typically requires more Portland cement, increasing CO2 emissions. However, using high-density aggregates can reduce the overall volume of concrete needed, potentially lowering the cement content and emissions.

Thank you for the detailed insights. Is there any additional information you would like to share?

Martin Rijnen: I recommend visiting resources like the betonhuis for comprehensive information on cement types and performance characteristics. Additionally, the Beton Innovatieloket offers insights into sustainable concrete innovations, though practical adoption often lags due to the lack of financial incentives.

C

Case Study

This appendix provides calculations and visualizations that are required for the system analysis and the actual design in the case study.

C.1. Soil Data

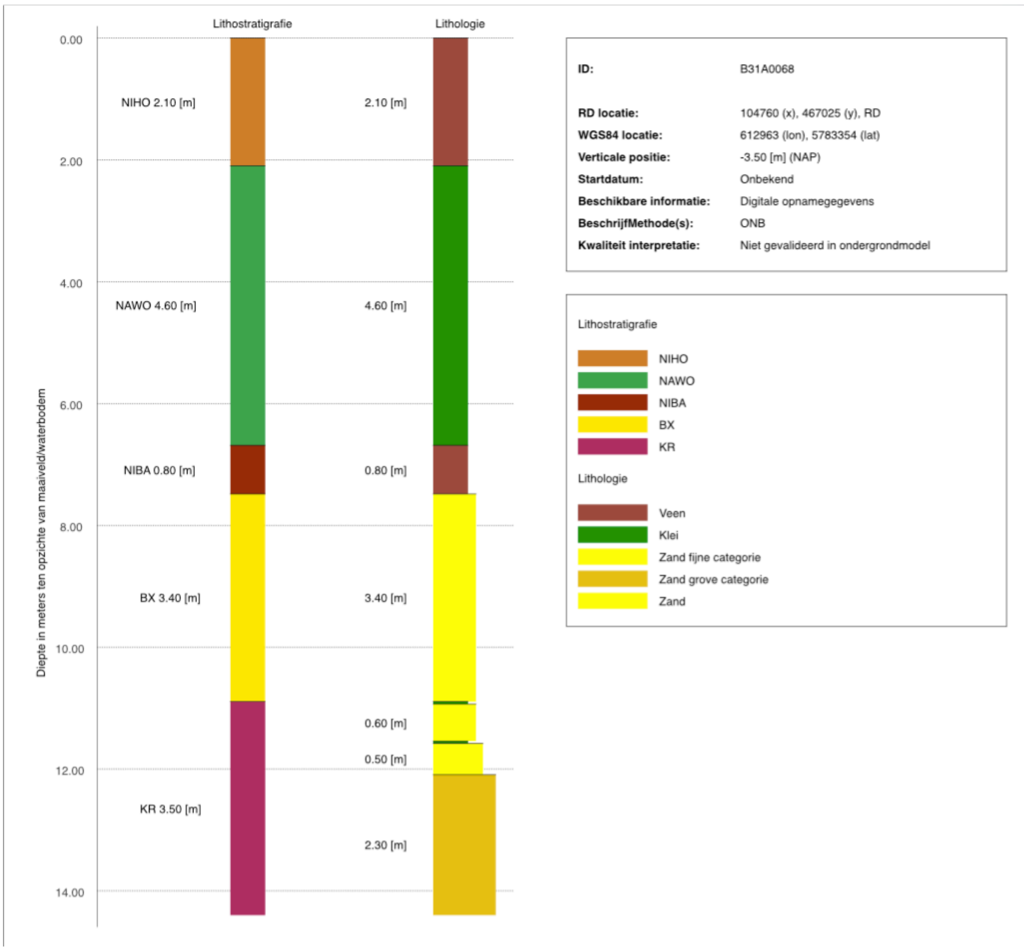
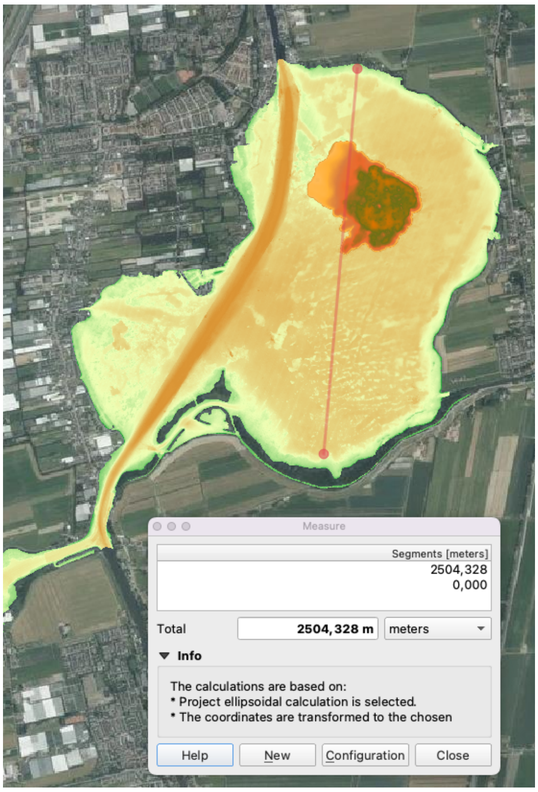


Figure C.1: CPT of the Braassemermeer
Source: From DinoLoket, 2024

C.2. Wind Fetches



(a) Longest Fetch

(b) Second Longest Fetch

Figure C.2: Fetches over the Braassemermeer

Input							Output					
richtingsbin	vanaf (graden)	tot (graden)	herhalingstijd [jaren]	windsnelheid (m/s)	fetch [m]	h [m]	A1	B1	A2	B2	Hs [m]	Tp [s]
NNE	11,25	33,75	10	11,3		3	0,16	0,00	0,08	0,00	0,00	0,00
NNE	11,25	33,75	100	12,3		3	0,14	0,00	0,06	0,00	0,00	0,00
NE	33,75	56,25	10	10,8		3	0,18	0,00	0,08	0,00	0,00	0,00
NE	33,75	56,25	100	11,3		3	0,16	0,00	0,08	0,00	0,00	0,00
ENE	56,25	78,75	10	12,4	605	3	0,14	0,03	0,06	0,01	0,15	1,55
ENE	56,25	78,75	100	13,4	605	3	0,13	0,02	0,05	0,01	0,16	1,61
E	78,75	101,25	10	12	405	3	0,15	0,02	0,07	0,01	0,12	1,37
E	78,75	101,25	100	12,8	405	3	0,14	0,02	0,06	0,01	0,13	1,41
ESE	101,25	123,75	10	10,1	250	3	0,19	0,02	0,09	0,01	0,08	1,11
ESE	101,25	123,75	100	10,5	250	3	0,18	0,02	0,09	0,01	0,08	1,13
SE	123,75	146,25	10	10,7	185	3	0,18	0,02	0,08	0,00	0,07	1,06
SE	123,75	146,25	100	11,3	185	3	0,16	0,01	0,08	0,00	0,08	1,08
SSE	146,25	168,75	10	10,3	170	3	0,19	0,02	0,09	0,00	0,07	1,01
SSE	146,25	168,75	100	10,9	170	3	0,17	0,01	0,08	0,00	0,07	1,04
S	168,75	191,25	10	16	350	3	0,10	0,01	0,04	0,00	0,15	1,51
S	168,75	191,25	100	17,1	350	3	0,09	0,01	0,03	0,00	0,16	1,55
SSW	191,25	213,75	10	16,8	435	3	0,09	0,01	0,03	0,00	0,18	1,63
SSW	191,25	213,75	100	17,6	435	3	0,08	0,01	0,03	0,00	0,18	1,67
SW	213,75	236,25	10	19,4	1000	3	0,07	0,02	0,03	0,01	0,30	2,18
SW	213,75	236,25	100	20,7	1000	3	0,07	0,02	0,02	0,01	0,32	2,24
WSW	236,25	258,75	10	17,4		3	0,09	0,00	0,03	0,00	0,00	0,00
WSW	236,25	258,75	100	18,1		3	0,08	0,00	0,03	0,00	0,00	0,00
W	258,75	281,25	10	20		3	0,07	0,00	0,02	0,00	0,00	0,00
W	258,75	281,25	100	21,2		3	0,06	0,00	0,02	0,00	0,00	0,00
WNW	281,25	303,25	10	16,9		3	0,09	0,00	0,03	0,00	0,00	0,00
WNW	281,25	303,25	100	18,1		3	0,08	0,00	0,03	0,00	0,00	0,00
NW	303,25	326,25	10	14,5		3	0,11	0,00	0,05	0,00	0,00	0,00
NW	303,25	326,25	100	15,2		3	0,11	0,00	0,04	0,00	0,00	0,00
NNW	326,25	348,75	10	14,6		3	0,11	0,00	0,04	0,00	0,00	0,00
NNW	326,25	348,75	100	15,3		3	0,10	0,00	0,04	0,00	0,00	0,00
N	348,75	11,25	10	14,8		3	0,11	0,00	0,04	0,00	0,00	0,00
N	348,75	11,25	100	16,5		3	0,09	0,00	0,03	0,00	0,00	0,00

Figure C.3: Historical Wind Data of the Braassemermeer

C.3. Wind Setup

$$\Delta h = \frac{\tau \cdot L}{\rho \cdot g \cdot d} \tag{C.1}$$

where:

- Δ h is the wind setup (change in water level, in meters).
- τ is the wind stress on the water surface (in Newtons per square meter, N/m^2).
- L is the fetch length, or the distance over which the wind blows across the lake (in meters).
- ρ is the density of water (approximately 1000 kg/m^3 for freshwater).
- g is the acceleration due to gravity (approximately 9.81 m/s^2).
- d is the average depth of the lake (4 meters).

$$\tau = \rho_{\text{air}} \cdot C_D \cdot U^2 \tag{C.2}$$

where:

- τ is the wind stress.
- ρ_{air} is the density of air (about 1.2 kg/m^3 at sea level).
- C_D is the drag coefficient, often taken as 0.0012.
- U is the wind speed at a certain height above the water's surface (in m/s).

Wind Direction N (North)

Table C.1: Calculated parameters for wind direction N (Bezuyen et al., 2007)

Parameter	Symbol	Value
Wind Speed	U_{10}	16.5 m/s
Wind Stress	τ	0.39 N/m^2
Fetch Length	L	2500 m
Average Depth	d	4 m
Wind Setup	Δh	0.025 m

Wind Direction WNW (West-Northwest)

Table C.2: Calculated parameters for wind direction WNW (Bezuyen et al., 2007)

Parameter	Symbol	Value
Wind Speed	U_{10}	18.1 m/s
Wind Stress	τ	0.47 N/m^2
Fetch Length	L	2200 m
Average Depth	d	4 m
Wind Setup	Δh	0.026 m

C.4. Calculations of Armour Stone Diameter

Direction	Wind Speed (m/s)	Fetch (m)	Depth (m)
NNE	12.3	2500	2, 3, 4, 5
NNW	15.3	2200	2, 3, 4, 5
NW	15.2	1500	2, 3, 4, 5
N	16.5	2500	2, 3, 4, 5
WNW	18.1	2200	2, 3, 4, 5

Table C.3: Input Parameters for Wave Calculations

Step 1: Calculate Significant Wave Height H_s

$$H_s = 0.241\left(\tanh(A1)\cdot\tanh\left(\frac{B1}{\tanh(A1)}\right)\right)^{0.87}\cdot\frac{U_{10}^2}{g} \tag{C.3}$$

Where:

$$A1 = 0.493\left(\frac{g\cdot h}{U_{10}^2}\right)^{0.75} \qquad B1 = 0.00313\left(\frac{g\cdot F}{U_{10}^2}\right)^{0.57} \tag{C.4}$$

Step 2: Calculate Peak Wave Period T_p

$$T_p = 7.519\left(\tanh(A2)\cdot\tanh\left(\frac{B2}{\tanh(A2)}\right)\right)^{0.37}\cdot\frac{U_{10}}{g} \tag{C.5}$$

Where:

$$A2 = 0.331\left(\frac{g\cdot h}{U_{10}^2}\right)^{1.01} \qquad B2 = 0.0005215\left(\frac{g\cdot F}{U_{10}^2}\right)^{0.73} \tag{C.6}$$

Step 3: Find the Dominant Wind Directions

Wave conditions for direction: NNE

	Depth 2 (m)	Depth 3 (m)	Depth 4 (m)	Depth 5 (m)
Hs (m)	0.28	0.29	0.30	0.30
Tp (s)	2.21	2.24	2.26	2.26

Wave conditions for direction: NNW

	Depth 2 (m)	Depth 3 (m)	Depth 4 (m)	Depth 5 (m)
Hs (m)	0.33	0.34	0.35	0.35
Tp (s)	2.35	2.39	2.41	2.42

Wave conditions for direction: NW

	Depth 2 (m)	Depth 3 (m)	Depth 4 (m)	Depth 5 (m)
Hs (m)	0.28	0.29	0.29	0.29
Tp (s)	2.14	2.16	2.17	2.18

Wave conditions for direction: N

	Depth 2 (m)	Depth 3 (m)	Depth 4 (m)	Depth 5 (m)
Hs (m)	0.38	0.39	0.40	**0.40**
Tp (s)	2.50	2.55	2.57	**2.58**

Wave conditions for direction: WNW

	Depth 2 (m)	Depth 3 (m)	Depth 4 (m)	Depth 5 (m)
Hs (m)	0.39	0.40	0.41	**0.42**
Tp (s)	2.53	2.58	2.60	**2.61**

Step 4: Calculation of Transition Breaker Parameter ($\xi_{\text{transition}}$)

The transition breaker parameter ($\xi_{\text{transition}}$) is calculated using the following formula:

$$\xi_{\text{transition}} = \left(\frac{c_{\text{pl}}}{c_{\text{s}}} \cdot P^{0.31} \cdot \sqrt{\tan(\alpha)} \right)^{\frac{1}{P+0.5}} \tag{C.7}$$

where:

- c_{pl} is the coefficient for plunging breakers.
- c_{s} is the coefficient for surging breakers.
- P is the permeability.
- α is the slope angle in degrees.

Calculation
Using the values:

c_{pl}	c_{s}	P	α
6.2	1	0.5	26.6°

The calculated transition breaker parameter ($\xi_{\text{transition}}$) is:

$$\xi_{\text{transition}} = 3.54$$

Step 5: Calculation of Irribarren Number

The Iribarren number (ξ) is calculated using the following formula:

$$\xi = \frac{\tan(\alpha)}{\sqrt{\frac{H}{\frac{gT^2}{2\pi}}}} \tag{C.8}$$

where:

- H is the wave height in meters.
- T is the wave period in seconds.
- α is the slope angle in degrees.
- g is the acceleration due to gravity (9.81 m/s^2).

Calculation
Using the values:

H_s (m)	T_p (s)	α (degrees)
0.42	2.61	26.6 (1:2)

The calculated Iribarren number (ξ) is:

$$\xi = 2.14$$

Step 6: Calculation of the Stability Number for Plunging Waves

The value of $\frac{H_s}{\Delta \cdot D_{n50}}$ for plunging waves is calculated using the following formula:

$$\frac{H_s}{\Delta \cdot D_{n50}} = 6.2 \cdot P^{0.18} \cdot \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \cdot \xi_{1.0}^{-0.5} \tag{C.9}$$

where:

- P is the permeability.
- S_d is the damage level.
- N is the number of waves.
- H_s is the significant wave height in meters.
- $\xi_{1.0}$ is the Iribarren number at wave height H_s.

Calculation
Using the values:

P	S_d	N	H_s (m)	$\xi_{1.0}$
0.6	2.0	7500	0.42	2.14

The calculated value of $\frac{H_s}{\Delta \cdot D_{n50}}$ is:

$$\frac{H_s}{\Delta \cdot D_{n50}} = 1.76$$

Step 7: Calculation of Nominal Stone Diameter (D_{n50})

The nominal stone diameter (D_{n50}) is calculated using the following formula:

$$D_{n50} = \frac{H_s}{\text{stability number} \cdot \Delta} \tag{C.10}$$

where:

- H_s is the significant wave height in meters.
- Δ is the relative density.
- stability number is the stability number.

Calculation
Using the values:

H_s (m)	Δ	stability number
0.42	1.60	1.76

The calculated nominal stone diameter (D_{n50}) is:

$$D_{n50} = 0.149m$$

C.5. Stone Classes

Class name	described in EN13383		d_{50} (cm)	d_{85}/d_{15}	d_{n50} (cm)	(2)	(3)
	range	(1)					
CP45/125	45/125 mm	0.4-1.2	6.3-9.0	2.8	6.4	20	300
CP63/180	63/180 mm	1.2-3.1	9.0-12.5	2.8	9	20	300
CP90/250	90/250 mm	3.1-9.3	12.5-18	2.8	12.8	20	300
CP45/180	45/200 mm	0.4-1.2	6.3-9.0	4.0	6.4	20	300
CP90/180	90/180 mm	2.1-2.8	11-12	2.0	9.7	20	300
LM$_A$ 5-40	5-40 kg	10-20	18-23	1.7	17	25	500
LM$_A$ 10-60	10-60 kg	20-35	23-28	1.5	21	32	550
LM$_A$ 40-200	40-200 kg	80-120	37-42	1.5	34	52	850
LM$_A$ 60-300	60-300 kg	120-190	42-49	1.5	38	57	950
LM$_A$ 15-300	15-300 kg	45-135	30-44	2.7	31	46	700
HM$_A$ 300-1000	300-1000 kg	450-690	65-75	1.4	59	88	1325
HM$_A$ 1000-3000	1-3 ton	1700-2100	103-110	1.4	90	135	2050
HM$_A$ 3000-6000	3-6 ton	4200-4800	138-144	1.2	118	177	2700
HM$_A$ 6000-10000	6-10 ton	7500-8500	167-174	1.2	144	216	3250

CP - Course gradings (1): range of W_{50} for category "A" (kg)
LM - Light gradings (2): Layer thickness 1.5 d_{n50} (cm)
HM - Heavy gradings (3): Minimal dumping quantity with layer of 1.5 d_{n50} (kg/m^2)

Figure C.4: Standard Gradings in EN13383 (Schiereck and Verhagen, 2019)

C.6. Brushwood Grids stacked with rock armour layer

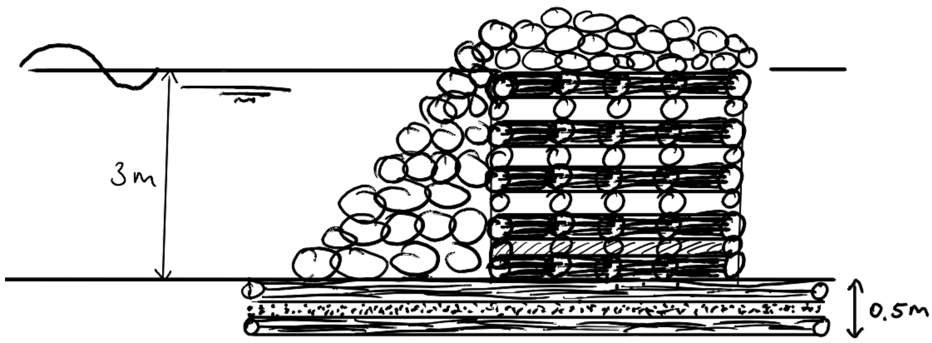


Figure C.5: Brushwood grids configuration with rock armour layer

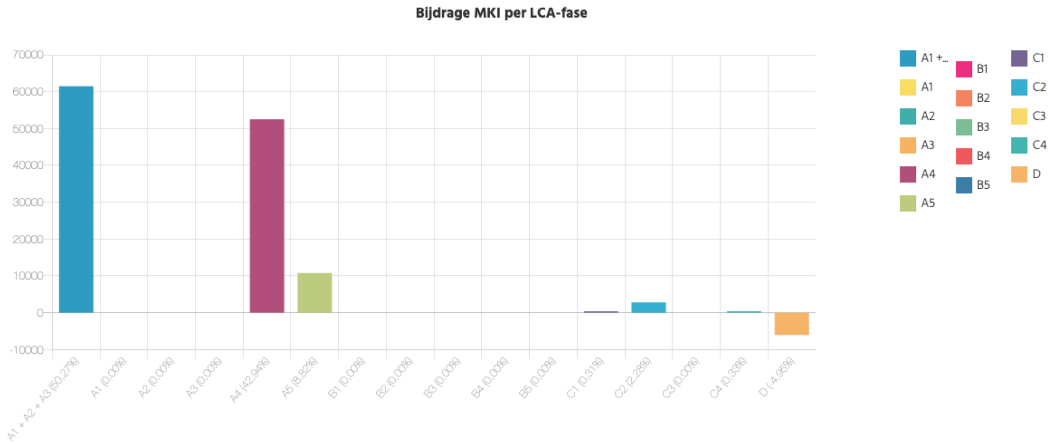
The armour layer dimensions for this breakwater design are assumed to be equal to those in the previously calculated design, so the structure is ensured to be able to withstand the incoming waveheight. This configuration uses dredged material for filling in combination with rubble rock, ensuring better stability. Additionally, a longer fascine mattress is required to provide adequate support and stability for the armour layer in front of the structure. The brushwood grids will be less exposed to weather, which will enhance the durability. However, the grids at water level will not be able to withstand much longer. This approach maintains the integrity of the structure while adapting the material use, offering a sustainable alternative without compromising on performance.

Table C.4: Overview of CO_2 emission/storage per component of breakwater with brushwood grids and armour layer

What	Quantity	Unit	kg CO_2/m^3	ton CO_2	DuboCalc
Willow branches stacked	10603	m^3	-92	-975.5	1059.31
Rubble Stone Armour layer	34500	m^3	22.26	768	44.03
Dredging material to fill grids	34397	m^3	0.98	33.7	30.07
Willow branches in fascine mattress	8400	m^3	-92	-772.8	23.82
Total CO_2 emission/storage				**-946.6**	**1157**

C.7. DuboCalc Scores

Rubble Mound Breakwater



Rubble Mound Breakwater

Naam

Rubble Mound Breakwater

Omschrijving

MKI-waardes

MKI inclusief toeslag (totaal)	158.321,94
MKI exclusief toeslag	122.287,30
MKI Toeslag	36.034,63
Bijdrage	100 %
Productiefase	61.473,04
Bouwfase	63.292,66
Gebruiksfase	0
Sloop- en verwerkingsfase	-2.478,39
CO2 (kg CO2-eq)	991.651,67

Figure C.6: DuboCalc scores Rubble Mound Breakwater

Brushwood Grids with Rock Armour Layer

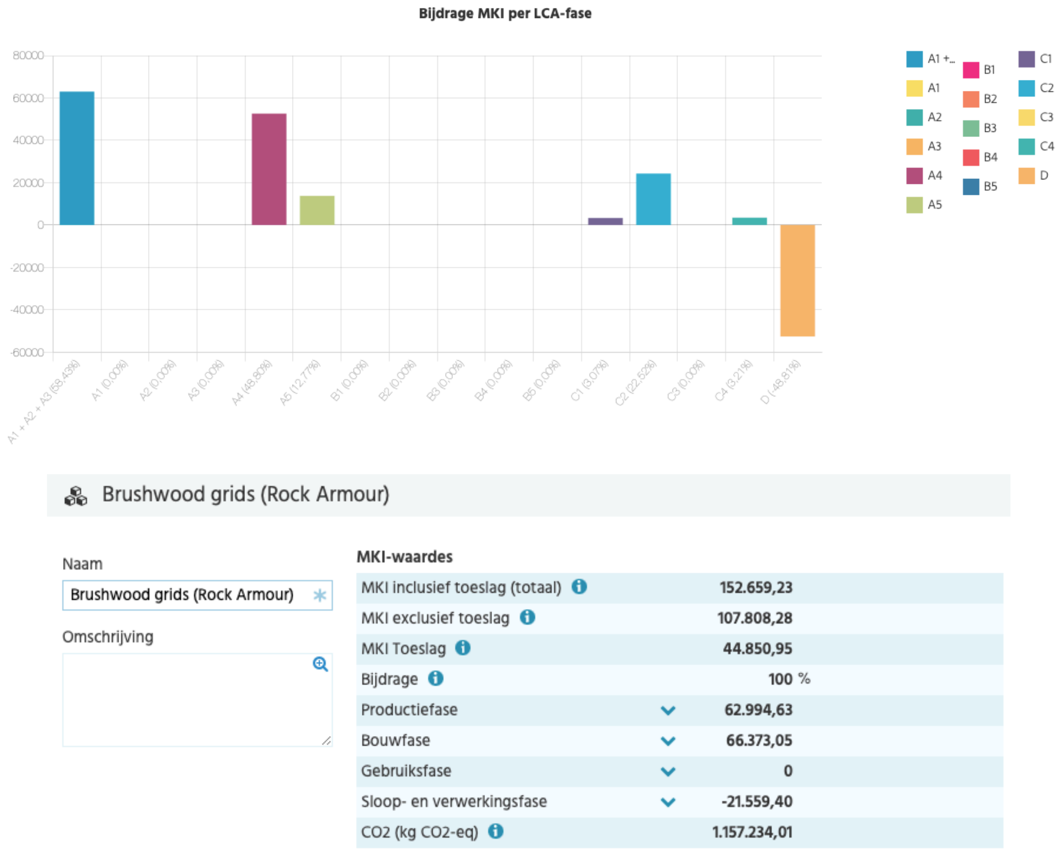


Figure C.7: DuboCalc scores Brushwood Grids with Rock Armour Layer